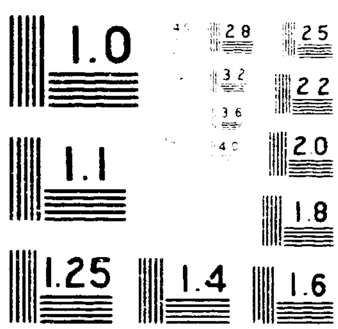
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Final Report

ANALYTICAL AND EXPERIMENTAL STUDY OF RESONANCE IGNITION TUBES

12 December 1973

JPL Contract No. PO 953563

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

FOREWORD

This report was prepared by the Rocketdyne Division of Rockwell International Corporation. The work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100. The contract period of performance was 21 December 1972 to 21 December 1973. The contract was administered for NASA by the Jet Propulsion Laboratory, whose Technical Manager was Mr. G. W. Kruger. The Rocketdyne Program Manager was Mr. J. Friedman, and Mr. L. Stabinsky functioned as the Rocketdyne Project Manager. Important contributions to the conduct of the program were made by the following Rocketdyne personnel: Messrs. P. D. Amdisen (system analysis), J. D. Waller and T. A. Heinz (design), and R. A. Avazian (experimental program).

ABSTRACT

The application of the gas-dynamic resonance concept was investigated in relation to ignition of rocket propulsion systems. Analytical studies were conducted to delineate the potential uses of resonance ignition in oxygen/hydrogen bipropellant and hydrazine monopropellant rocket engines. Experimental studies were made to 1) optimize the resonance igniter configuration, and 2) evaluate the ignition characteristics when operating with low temperature oxygen and hydrogen at the inlet to the igniter.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

The application of the gas-dynamic resonance heating concept for ignition of rocket engines was investigated. The investigation was divided into two tasks. Task I was an analytical study to determine potential advantages of the resonance igniter over state-of-the-art ignition methods used in several specific propulsion systems. Task II was an experimental investigation primarily directed toward: (a) the optimization of the resonance igniter configuration for subsequent operation with low-temperature oxygen and hydrogen, and (b) the characterization of the resonance ignition performance using oxygen/hydrogen propellants at low temperatures.

During the Task I study considering ignition oxygen/hydrogen bipropellants, it was found that for the Space Shuttle Auxiliary Propulsion System, use of the resonance igniter would provide an ignition system weight savings of approximately one-half when compared to the weight of the conventional spark ignition system. For the Space Shuttle Main Engine resonance ignition would result in a weight savings of about 20 percent. For the Advanced Maneuvering Propulsion System (AMPS) aerospike engine where 24 combustion chambers have to be ignited individually, the resonance igniter, again, would provide weight savings over the augmented spark ignition method of about 15 to 30 percent depending on the type of resonance igniter design. However, in all of the above cases, the use of resonance ignition would result in high reliability due to its mechanical simplicity and would eliminate the problems of radio frequency interference associated with spark ignition.

The application of resonance heating for ignition of hydrazine monopropellant was briefly studied for two applications: (1) a direct attitude control system and (2) the momentum wheel. For both applications it was found that resonance ignition would not be suitable due to the extremely short duty cycle requirements, and the need for hydrazine gasification prior to injection into the resonance igniter.

During Task II, a series of experiments were performed using hydrogen only to determine the optimal critical dimensions of the resonance igniter when operating with low temperature O_2/H_2 propellants. As anticipated, it was found that these critical dimensions differed substantially from the values found during a previous effort where the resonance igniter was optimized for ambient propellant operation. Upon completion of the geometry optimization tests, as series of ignition tests were conducted with oxygen and hydrogen having inlet temperatures ranging from 294 K (530 R) to 142 K (256 R). All tests conducted resulted in successful ignitions. The Task II program demonstrated that the resonance igniter can be utilized as a reliable ignition method for rocket engine propulsion systems operating with oxygen and hydrogen propellants stored at cryogenic temperatures.

INTRODUCTION

The objective of this contract was to study the application of gas-driven resonance tubes to the ignition of low-temperature oxygen/hydrogen bipropellant and of hydrazine monopropellant in propulsion system concepts. The applications of resonance ignition considered were for spacecraft main propulsion and attitude control. The study included: (1) a comparison of resonance ignition with state-of-the-art ignition systems, (2) the identification of critical components of these ignition systems, and (3) the optimization of design and characteristics of these critical components. To attain these objectives, the program was divided into two tasks. Task I is a system analysis which entails the preparation of preliminary design concepts and the screening of the concepts. Task II is an experimental and analytical study of the attractive screened concepts.

This report covers the results of both Task I and Task II efforts.

DESCRIPTION OF CONCEPT

The resonance igniter is a novel type of igniter that is based on the phenomena of gas-dynamic resonance. It has the advantage of requiring no external energy sources or chemically active surfaces. The operation of the resonance igniter depends solely on the pressure energy of the propellant system.

The resonance igniter consists of four major components: (1) a sonic nozzle, (2) a resonance cavity, (3) a mixing chamber, and (4) a restriction located at the exit of the mixing chamber. The resonance igniter component arrangement is shown schematically in Fig. 1.

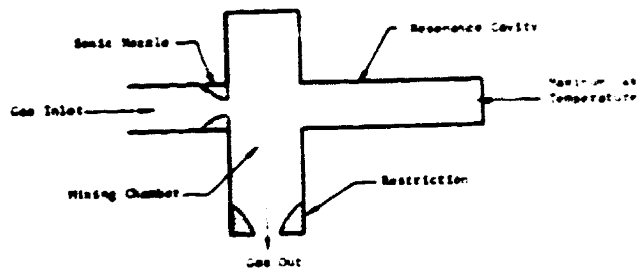

Figure 1. Resonance Igniter Schematic

As shown in the previous figure, a gas is introduced into the resonance igniter, it flows through the sonic nozzle, expands into the mixing chamber, and flows out of the mixing chamber through the restriction. With proper geometrical and size considerations, a fraction of the incoming gas will be cyclically compressed and expanded within the closed-end resonance cavity. The net effect of the cyclic compression expansion process (resonance) is a temperature increase in the gas residing within the resonance cavity, the maximum gas temperature occurring at or near the closed end of the cavity.

The basic operation of the resonance igniter thus depends upon heating a gas to a temperature sufficiently high to cause ignition.

There are a number of methods of utilizing the resonance gas heating phenomenon for ignition purposes, the principal ones being listed and briefly described below:

1. Opposed fuel and oxidizer flow method. In this method, one of the gases (either the fuel or oxidizer) undergoes resonance heating, and the other (either the oxidizer or fuel) fluid is forced to flow into the device by opening a valve located at the tip of the cavity, causing ignition at the interface of the two gases and establishing combustion in the mixing chamber (Fig. 2a).
2. Premixed fuel and oxidizer method. Here both the fuel and oxidizer are premixed prior to flowing into the sonic nozzle. Ignitions occur in the resonance cavity and combustion is sustained in the mixing chamber (Fig. 2b).
3. Hot flow extraction method. In this method, a small portion of the entering gas is tapped off from the end of the resonance cavity. The extracted gas, being at high temperatures, can be used for ignition purposes outside of the resonance device proper (Fig. 2c).
4. Surface heating method. Here a gas is introduced into the device and the closed end of the resonance cavity is heated (the closed end being made of a conductive material). Ignition can be made to occur at the external side of the hot surface (Fig. 2d).

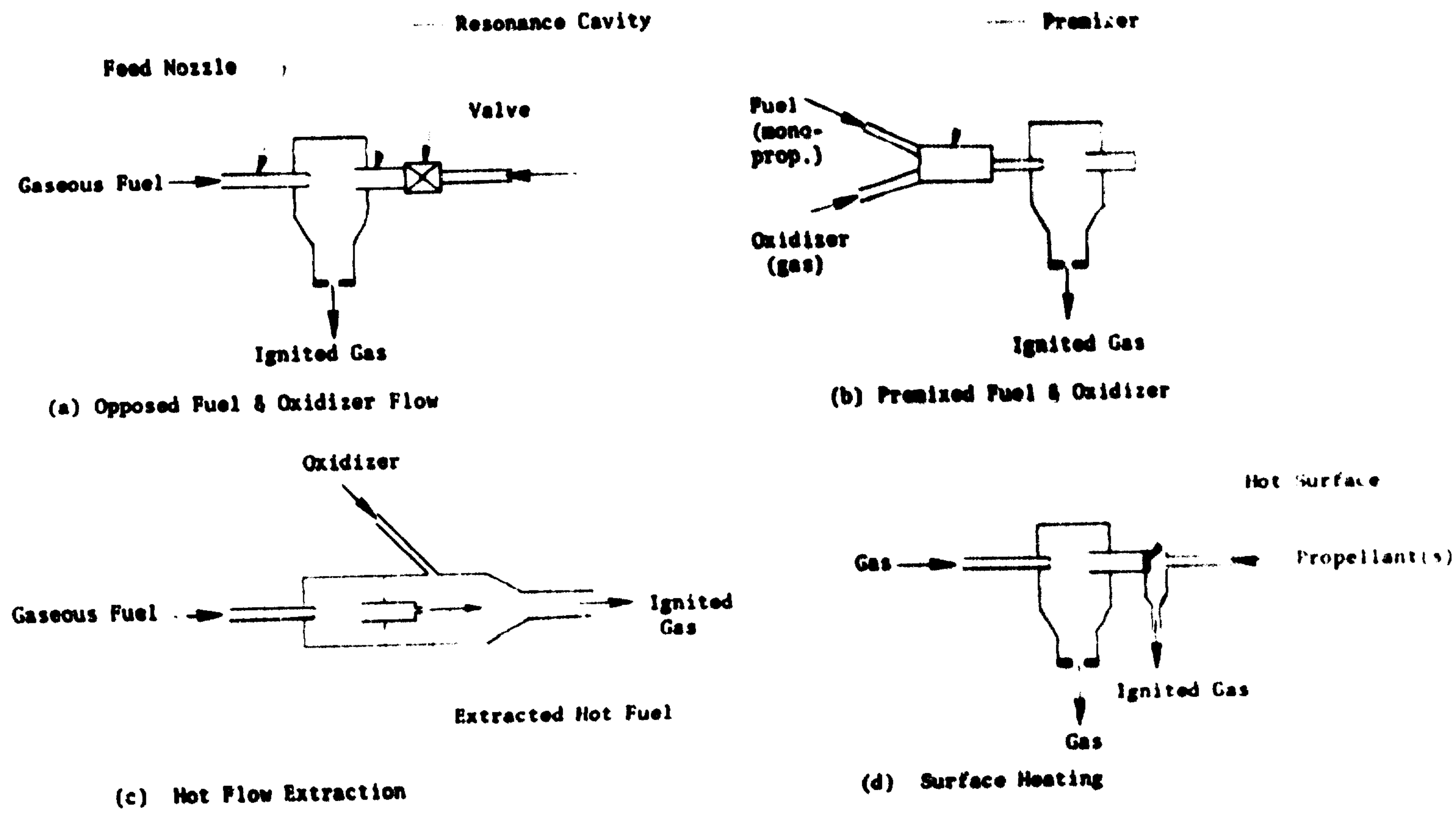

Figure 2. Resonance Ignition Methods

Each of the resonance concepts described above can be used for bipropellant ignition provided that one of the propellants is in the gaseous state. For monopropellants, the resonance ignition concepts can be used only if the monopropellant is in the gaseous state or if it is atomized and carried in a secondary gas (such as helium or nitrogen). The surface heating method by resonance of a secondary gas can be used in conjunction with liquid monopropellants by bringing the monopropellant in contact with the hot surface to start the decomposition process.

The application of a given resonance ignition concept depends upon various considerations such as the propellant feed system characteristics, weight, and ignition delay requirements.

TECHNICAL DISCUSSION

TASK I - SYSTEM ANALYSIS

The application of the resonance igniter was studied in relation with three rocket propulsion systems using oxygen/hydrogen propellants, and a brief investigation was performed for the resonance ignition of two rocket propulsion systems using hydrazine as a monopropellant.

The rocket propulsion ignition systems investigated are tabulated below.

TABLE 1. ENGINE IGNITION SYSTEMS

1.	Space Shuttle Main Engine (SSME)	O_2/H_2 Bipropellant
2.	Space Shuttle Auxiliary Propulsion Engines (SS/APS)	
3.	Advanced Maneuvering Propulsion (AMPS)	
4.	Direct Attitude Control System	Hydrazine Monopropellant
5.	Momentum Wheel	

Each of the above systems will be discussed below.

SPACE SHUTTLE APPLICATIONS

In its present configuration the SSME uses oxygen and hydrogen as propellant, and for the purposes of this study, it was assumed that the APS will also use the same propellants.

To evaluate the potential application of the resonance igniter in the SSME and APS, the general characteristics of the O_2/H_2 spark igniter system were collected. The data were obtained from in-depth studies reported in Ref. 1 and 2, and are summarized in the following paragraphs.

1. SSME and APS Spark Igniter Characteristics

A summary of the SSME preburner, main chamber, and APS igniter characteristics is presented in Table 2. A schematic of the APS igniter is shown in Fig. 3 and a drawing of the system is shown in Fig. 4. The SSME preburner and main chamber igniters are shown schematically and diagramatically in Fig. 5.

The propellant supply represents a major difference between the APS and SSME systems, since the APS is pressure fed while the SSME is pump fed. Hence, the SSME operation has an extended (3.0 sec) start transient beginning at low tank head pressures and bootstrapping up to very high pump discharge pressures.

Each igniter uses an integral plug/exciter which provides a 10-mj energy spark from a 28-vdc power source. This unit weights approximately 1 pound, and two are required for each igniter to enhance ignition reliability through redundancy. Spark frequencies from 50 to 200 Hz are provided and ignition is achieved by the second spark after a combustible mixture is introduced. Hence, ignition delays of only 10 to 40 msec occur.

Propellant sequencing on the APS is achieved by using the main propellant valves and appropriate orificing and manifold design. Hence, no weight penalty for igniter valves is incurred. However, on the SSME, a special three-way valve is required to achieve the proper sequencing thereby increasing the hardware complexity and cost.

The major penalty associated with a spark igniter is therefore associated with the electrical complexity and power consumption. The APS draws 8 watts of power per plug for 0.1 sec for each start. With the requirement for 10^6 starts, this requires 444 watt-hours ($2x8x0.1x10^6/3600$ = 444 watt-hr) for the entire mission. The SSME igniter draws 30 watts of power per plug for 3.5 seconds for each start. With two preburners and one main chamber, each with two plugs, the SSME power requirement is 180 watts instantaneous and 0.75 watt-hr per start.

TABLE 2. TYPICAL SPARK IGNITER CHARACTERISTICS

	APS Engine	SSME (ASI) Preburners (Fuel)	SSME (ASI) Main Chamber
Ignition Mixture Ratio, o/f	1.0	0.83	0.75
Ignition Supply Pressure (H_2/O_2) psia	375/375	24.4/20.4	34.6/28.5
Ignition Chamber Pressure, psia	111	20.1	25.6
Ignition Injection Temp. (H_2/O_2), R/R	250/375	80/165	80/165
Ignition Flowrate, lb/sec	0.020	0.028	0.083
Ignition Response (from start of propellant flow), msec	10	30	30
Mainstage Mixture Ratio, o/f	0.7	0.67	0.67
Mainstage Supply Pressure (H_2/O_2) psia	375/375	5769/6028	6155/4059
Mainstage Chamber Pressure, psia	300	5420	3386
Mainstage Injection Temp. (H_2/O_2),R/R	250/375	296/205	93/187
Mainstage Flowrate, lb/sec	0.015	1.88	1.67
Mainstage Response (signal to 90% P_c) msec	40	3000	3000
Spark Frequency, HZ	200	75	75
Power Consumption (ea) watts	8	30	30
Power Duration per Start, sec	0.1	3.5	3.5
Input Voltage, VDC	28	28	28
Output Voltage, VDC	10K	10K	10K
Spark Energy, mj	10	10	10
Igniter Chamber Diameter/Throat), in.	0.7/0.25	1.0/1.0	1.0/1.0
Integral Plug/Exciter Weight (2), lb	1.40	2.66	2.66

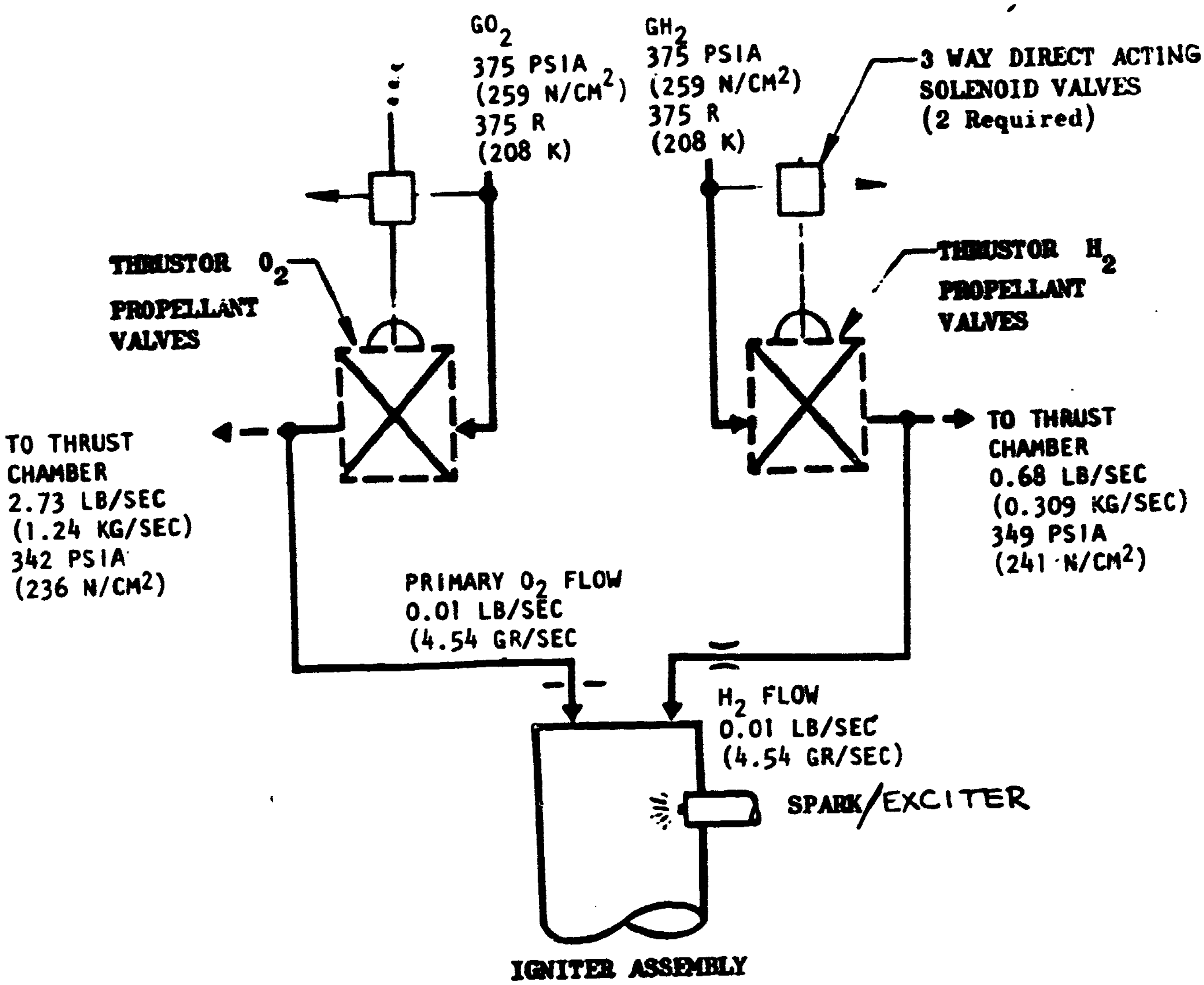

Figure 3. Baseline Spark Igniter Flow Schematic

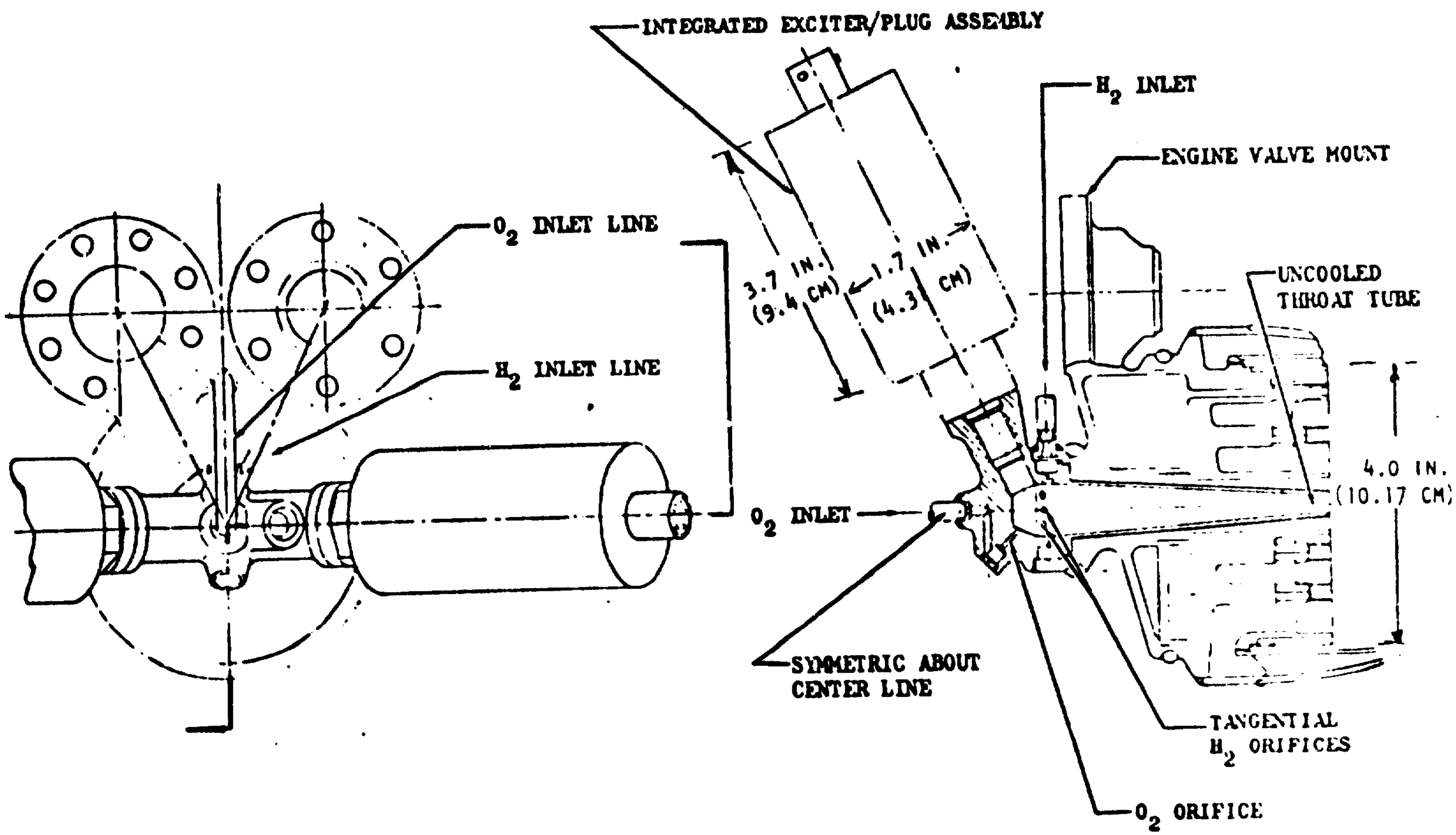

Figure 4. APS Baseline Spark "Ignition Only" System

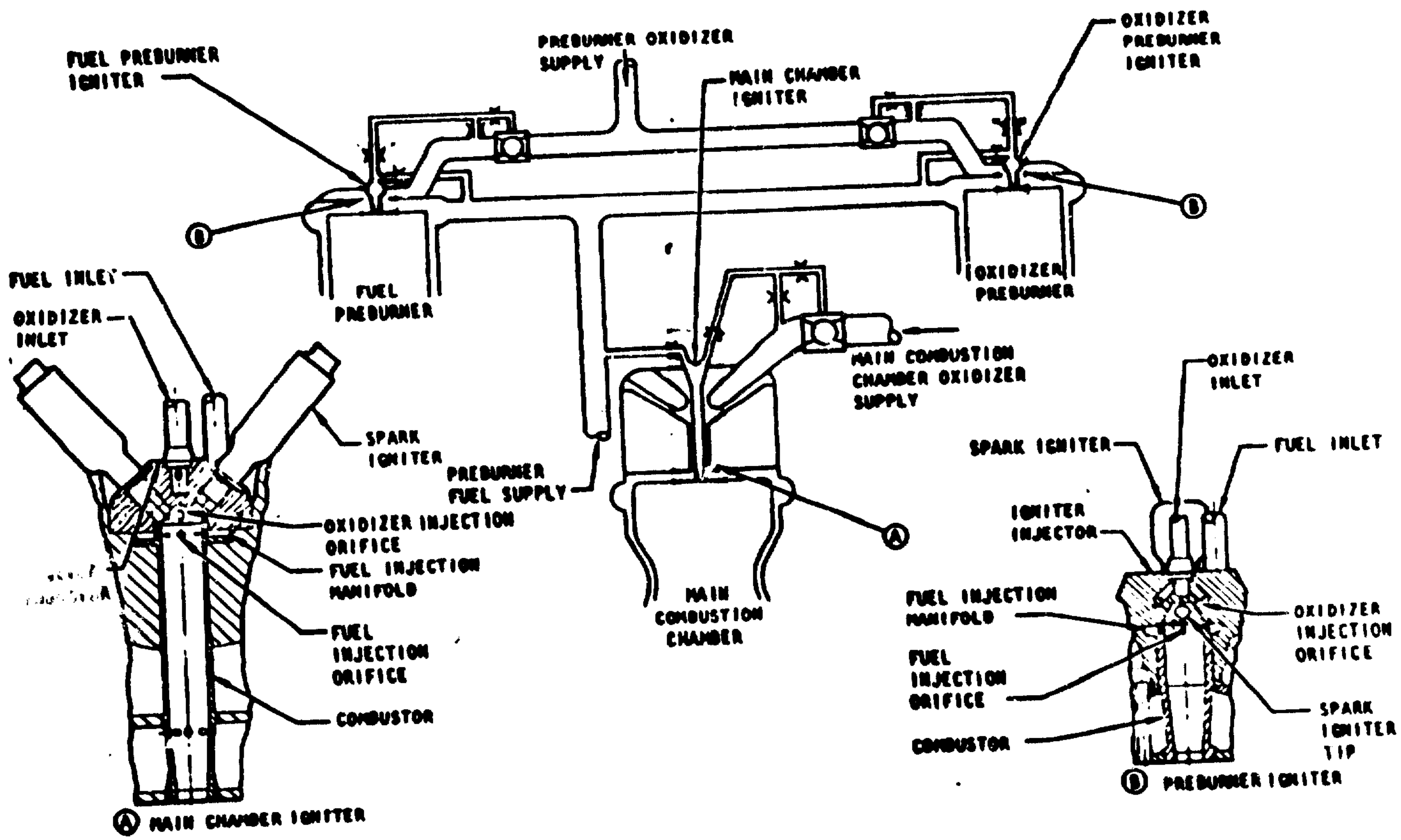

Figure 5. SSME Igniter Flow System Schematic

2. SSME and APS Resonance Igniter System

During this phase of the study, the potential of replacing the spark ignition system in the Space Shuttle with a resonance ignition system was investigated. Since the igniter provides a hot-gas torch for engine ignition, it was assumed that the hot-gas flowrate required of the resonance igniters would be the same as those indicated on Table 2.

The operation of the resonance igniter necessitates that, for fast response and high-resonance temperature, the hydrogen be in the gaseous state at stagnation pressures at least equal to 150 psia (103 N/cm^2). The stagnation pressure requirement is due to the fact that the resonance heating process will only occur if a pressure ratio of approximately 10 is available, and the ignition must be demonstrated at sea level. Consequently, the resonance igniter could not operate under tank-head start as in the case of the preburner and main chamber ASI's. For this study, it was assumed that the propellant for preburner and main chamber resonance igniters would be made available either from tanked conditions or from a gas conditioner as used in the APS. To achieve mainstage conditions, the propellants could be supplied (by bootstrapping) from the engine pump system.

3. SSME and APS Resonance Igniter Concept Selection

Of the four resonance igniter concepts shown in Fig. 2, the hot-flow extraction and surface-heating methods have distinct disadvantages with respect to the SSME and APS application.

In laboratory tests performed with the hot-flow extraction concept (Ref. 2) using ambient temperature hydrogen with an inlet stagnation pressure of 200 psia (138 N/cm^2), it was noted that in order to achieve a hydrogen temperature of 1460 R (811 K) (deemed as the required ignition temperature of O_2/H_2) only 1 percent of the inlet hydrogen flow could be extracted. Higher flow-removal rates considerably reduced the temperature. One percent of the total inlet flow meant that only 0.001 lb/sec (0.454 gr/sec) could be used for ignition purposes. It

was also observed that 3 to 4 seconds were required for the removed hydrogen to reach equilibrium temperatures. Although this time interval could be reduced with additional experimental efforts, a major drawback to the valveless igniter is the fact that extremely small orifices of the order of 0.005 inch (0.0127 cm) in diameter would be required to control the hydrogen flow being removed from the resonance cavity. Thus, the possibility of contaminants plugging orifices of this size, coupled with the relatively long flow duration, precludes the application of the hot-flow extraction method for the Space Shuttle ignition.

To achieve ignition by means of a hot surface, the metal-surface temperature must be at a higher temperature than the normal ignition temperature obtained, say, by uniformly heating the premixed propellants (Ref. 3). The required surface temperatures for low mixture ratio O_2/H_2 ignition could not be found in the literature, however, it is estimated (based on the data in Ref. 3) that the surface temperature would have to be of the order of 2000 R (1110 K) to achieve ignition of O_2/H_2.

Although this temperature could be achieved at the tip of a gas resonance device, heat removal by conduction from the resonance cavity would substantially increase the time required to achieve the required ignition temperature. It is anticipated that the use of this concept for APS ignition, where 40-msec response is required, would be eliminated on the basis of excessive surface heating time.

The opposed and premixed propellants resonance ignition methods appear to be the most attractive concepts for application to the SSME and APS on the basis of proven practicality, reliability, and response time. Of these two concepts, the opposed-flow design has the fastest ignition response characteristics, whereas the premixed-flow design offers the advantage of lighter weight due to the elimination of the coupled oxidizer valve. Using ambient-temperature oxygen and hydrogen, experiments performed with premixed resonance igniters indicated that reliable ignition could be achieved 600 msec after introducing the propellant mixture into the igniter (Ref. 4). Similar experiments with opposed-flow resonance igniters showed that ignition could be achieved within 20 to 40 msec after activation

of the hydrogen inlet valve (hydrogen being sequenced first into the igniter). A detrimental aspect of the premixed resonance igniter found during the experiments was that the mixed propellant feed system, characterized by propellant line size and length, influenced the igniter performance. Although the cause of the flow feedback was not fully investigated, it is hypothesized that ignition in the low subsonic portion of the inlet nozzle boundary layer may have occurred. Additional development will be required to eliminate the influence of feed system characteristics on the premixed resonance igniter performance.

Based on the above discussion, the opposed-flow resonance igniter method was chosen as the concept warranting further evaluation for the Space Shuttle application because of: (1) demonstrated high reliability in earlier tests with ambient propellants, and (2) fast response which would make the development compatible for both APS and SSME requirements.

4. SSME and APS Resonance Igniter Preliminary Design

The following discussion describes a preliminary design for Space Shuttle resonance igniters.

The igniter assembly shown in Fig. 6 is a self-contained device designed to provide an ignition source for Space Shuttle H_2/O_2 attitude control thrusters and main engines. The device derives ignition of igniter propellants through heat generated by resonance compression of hydrogen in a tuned quartz-lined cavity. Critical features for this preliminary design were obtained from prior optimization studies and tests conducted by Rocketdyne (Ref. 4).

The resonance igniter assembly is intended to replace the current augmented-spark igniters on attitude thrusters, preburners and main thrust chambers, and is similarly intended to be mounted through the center of the respective injector bodies. The resonance igniter is composed of a sonic *fuel injector nozzle*, a stepped *resonance cavity*, a pressure-actuated igniter oxidizer valve, a mixing chamber, a sonic downstream *restrictor nozzle*, and a connecting *duct*.

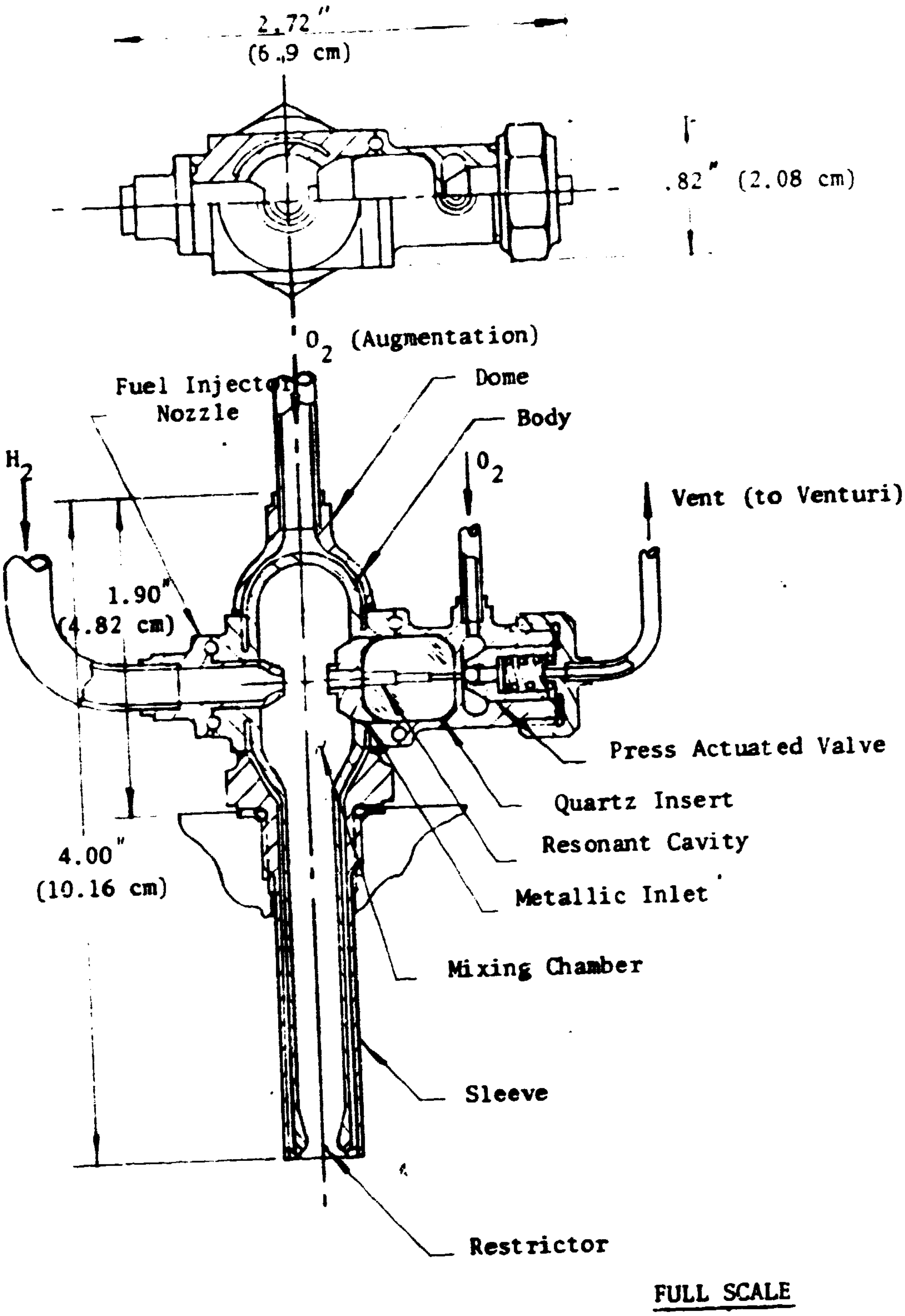

Figure 6. APS or Preburner Autoigniter Assembly

The resonance igniter operates in the following manner. Fuel from the igniter fuel valve (main fuel valve, APS) is injected through the sonic *fuel injector* nozzle. The fuel is heated by resonance compression at the end of the resonant cavity. Oxidizer from the igniter oxidizer valve (main oxidizer valve, APS) opens the pressure-actuated igniter oxidizer valve. The oxidizer mixes with the heated fuel in the cavity and ignites. Oxidizer and fuel mixing (low mixture ratio) and combustion is sustained in the mixing chamber. Temperature of the igniter gas is increased by addition of oxidizer downstream of the *restrictor* nozzle providing a torch for main chamber ignition.

The sonic *restrictor* controls the back pressure in the mixing chamber. Dimensions of the *restrictor, fuel injector nozzle, resonance cavity,* and *gap* between the fuel nozzle and resonance cavity are closely related and are optimized to produce the desired resonant heating of the initial fuel gas. Based on previous optimization studies, the following parameters were used for this design.

Gap/injector nozzle diameter = 3.426

Fuel injection pressure/mixing chamber pressure = 5.2

Resonance cavity inlet diameter/injector nozzle diameter = 1.3

The igniter assembly shown in Fig. 5 is designed for producibility; however, standard machining practices may be utilized for prototype fabrication.

A one-piece cast body forms the mixing chamber, restrictor nozzle, and connecting duct; opposed apertures provide mounts for the fuel nozzle and resonance cavity. A welded dome and sleeve close off the convective coolant jacket; the sleeve is threaded for assembly with the thruster injector body.

The resonance cavity is formed by machined contours in both a metallic inlet section and quartz insert. The inlet section has a sharply stepped contour to prevent boundary layer thickening and subsequent standoff shock pattern. The quartz

insert minimizes heat loss. The mating surfaces of the inlet, insert, and housing are lapped to prevent cavity leakage. Compliance is provided in the housing by the weld joint design. The cavity components are preloaded on assembly.

The pressure-actuated oxidizer valve configuration is similar to one which has been successfully tested. A metallic ball seat has been added to the Teflon poppet to provide longer life. The poppet nose retracts the ball and a metallic insert provides seat loading.

The fuel injection nozzle is removable for turning if necessary. A weld ring is used on subsequent assembly.

The configuration shown was sized for both the APS thrusters and main engine preburners. A main chamber igniter is obtained by scaling up the assembly ($\sim$2X) to accommodate higher propellant flowrates.

Igniter propellants for all systems are assumed to be obtained from the APS pressurized feed system. Both pressures and temperatures encountered during the initial stages of the main engine tank-head start are below established limits for reliable resonance igniter operation. Main engine igniters bootstrap to supply propellants during mainstage. A schematic of the required system is shown in Fig. 7.

Assumed nominal conditions include:

Fuel supply pressure = 375 psia (259 N/cm^2)

Oxidizer supply pressure = 375 psia (259 N/cm^2)

Fuel injection temperature = 250 R (139 K)

Oxidizer injection temperature = 375 R (208 K)

Oxidizer augmentation increases torch temperature and c*, improving igniter reliability performance. Depending upon detailed system balance calculations, wall temperatures should remain well within the service temperature range

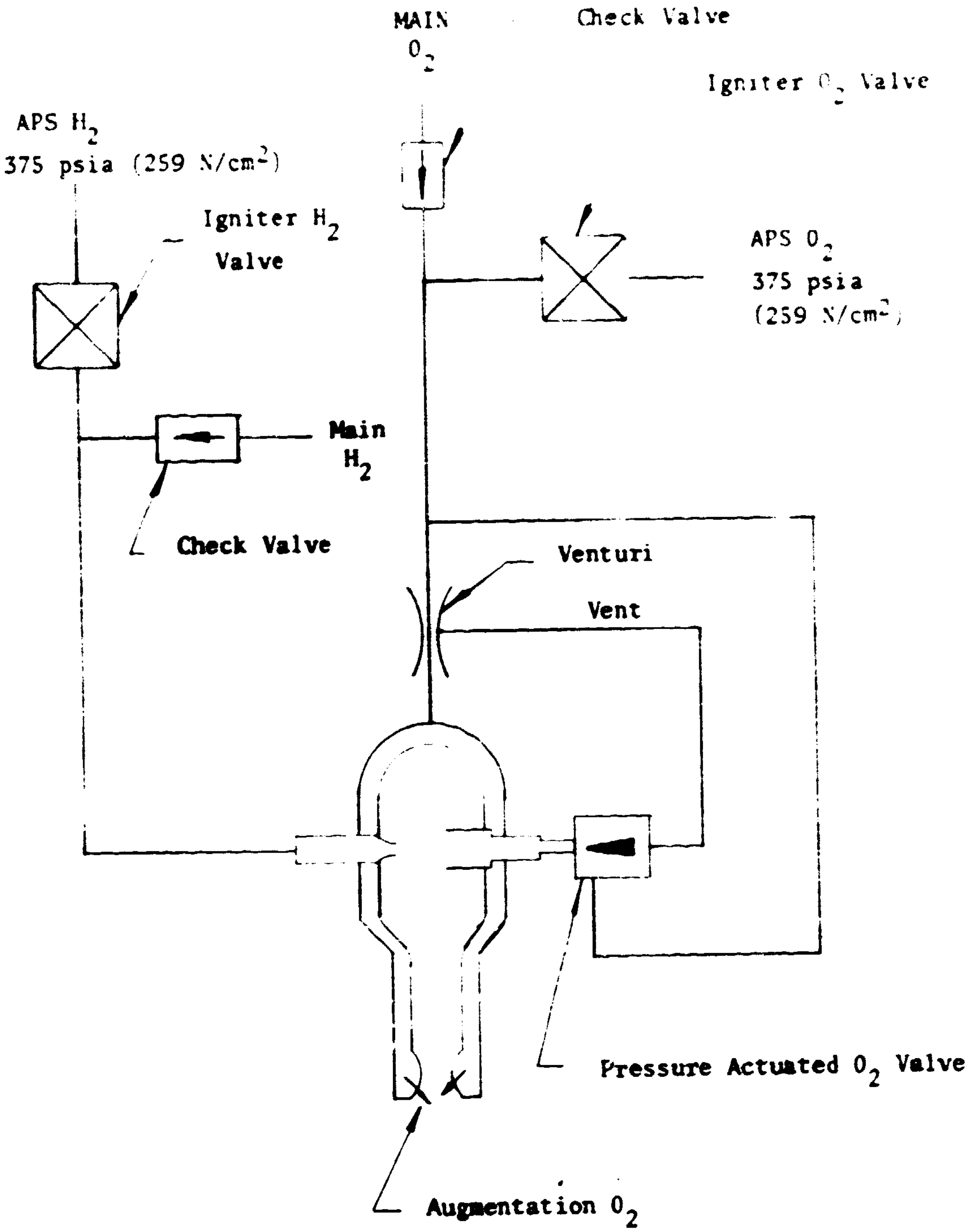

Figure 7. Preburner Igniter System

of cobalt-Ni alloys. Streaking in the high-temperature restriction nozzle is minimized by the high L/D of the connecting duct.

It has been shown that an internal igniter mixture ratio of 1.5 minimum is required for reliable ignition when using oxidizer augmentation. A corresponding gas temperature of 2860 R (1590 K) imposes a large heat load on the aft igniter wall and restrictor. A stabilized temperature as high as 2260 R (1255 K) is expected in the restrictor nozzle due to the low c_p (specific heat at constant pressure) of the oxidizer coolant. This temperature can be reduced by incorporating a cavitating restriction in the igniter fuel inlet line to decrease post-ignition mixture ratio with increasing back pressure.

5. Space Shuttle Ignition System Study - Conclusions

The weights for the resonance ignition systems discussed in the previous paragraphs are given in Table 3. Also shown in the table are the corresponding weights for the spark ignition system. For both ignition systems it was assumed that the Space Shuttle APS will use O_2/H_2 propellants which will be drawn from the tanks in the liquid state and be pressurized and gasified (to the conditions shown in Table 2) prior to entering the igniters. As can be seen from Table 3, the APS resonance igniter system weight is less than half the weight of the spark igniter system. The principal weight advantage of resonance ignition being due to the elimination of the electrical energy supply system, which for the purposes of this study, was assumed to be a nickel-cadmium battery weighing 0.38 lb (172 gr) per ampere-hour. The advantages of the APS resonance igniter system over the spark igniter system is further emphasized when considering that approximately 40 auxiliary propulsion engines will be used in the orbiter Space Shuttle vehicle, and that the radio interference problem due to sparking would be eliminated.

The weights of the SSME igniter system shown in Table 3 are the total weights for the fuel preburner, oxidizer preburner, and main chamber igniters. As in the case of the APS igniter system, it was assumed that the SSME igniters would be supplied

TABLE 3. SPACE SHUTTLE IGNITER SYSTEM SUMMARY

RESONANCE IGNITER SYSTEM	APS WEIGHT.LB.	SSME WEIGHT. LB.	SPARK IGNITION SYSTEM	APS (ASI) WEIGHT. LB.	SSME (ASI) WEIGHT LB.
Igniter	0.4	2.6	Battery	6.05	0.75
Valves	3.5	10.5	Plug/Exciter	1.40	7.98
Check Valves	1.0	3.0	Chamber Body	3.85	11.55
Total Weight-lb.	4.9	16.1		11.30	20.28

with propellants having inlet properties similar to those for the APS. Under these circumstances, Table 3 indicates that the SSME resonance igniter system would weigh approximately 20 percent less than the spark igniter system. This weight advantage would be negated if separate propellant storage tanks were to be provided for the igniter start. However, with an O_2/H_2 APS, the main engine ignition start could be supplied from a common gas conditioning unit, and resonance ignition would be competitive with spark ignition.

ADVANCED MANEUVERING PROPULSION APPLICATIONS

An O_2/H_2 ignition system study was conducted for the Advanced Maneuvering Propulsion System (AMPS) aerospike engine (Ref. 5). The AMPS aerospike engine has a nominal thrust of 25,000 pounds (1.11×10^5 N). There are two engine systems being considered. One of these is a single-panel aerospike engine (a demonstrator thrust chamber configuration) with a chamber pressure and area ratio of 750 psia (518 N/cm^2) and 110:1, respectively. The second engine system has a double-panel thrust chamber cooling circuit, and has a chamber pressure and area ratio of 1000 psia and 200:1, respectively. The AMPS is designed to operate in vacuum and has the capability of 5:1 throttling and off-design mixture ratio operation. The aerospike engine combustion chamber is made up of 24 individual segments, each of which must be ignited simultaneously.

The purpose of the study was to (1) identify ignition methods suitable for use in the AMPS aerospike engine, (2) assess the techniques in terms of relative weight, complexity (i.e., number and/or type of components) and technology status, and (3) select an approach to be used in the engine detail design phase. Emphasis was directed to methods currently in use or having sufficient experimental substantiation to ensure success in an operational system. Tradeoffs were, of necessity, qualitative, though the objective of achieving a reliable, lightweight ignition system as the culmination of a low-risk development effort was utilized as the basic selection guideline.

Various ignition system designs based upon demonstrated technology are applicable to the AMPS aerospike thrust chamber. The most promising approaches are listed in Table 4. Propellants for the resonance ignition systems were assumed to be supplied from high-pressure GO_2 and GH_2 sources. It may, however, be possible to develop a low-pressure configuration which utilizes propellants tapped off the main propellant flow circuits.

TABLE 4. O_2/H_2 IGNITION TECHNIQUES

Augmented Spark Ignition
Resonance: Opposed fuel and oxidizer flow
Resonance: Premixed fuel and oxidizer flow
Combustion Wave
Third Propellant: GF_2, CTF, TEA
Catalyst

The use of a third propellant or a catalyst bed were eliminated because of potential problems in the development of a multiple-start, long-life configuration.

System Evaluation

The ignition methods best suited to the AMPS engine are: (1) augmented spark ignition, (2) resonance ignition, and (3) combustion wave. The principal disadvantages of current versions of the resonance and combustion wave ignition systems is the requirement for high-pressure tanks that must be recharged during engine operation. However, the high reliability of such devices has been proven in the Atlas vernier and J-2 engines. The need for rechargeable start tanks is not, therefore, a basis for rejection of a concept, though the simplicity and weight advantage of tapoff systems is certainly beneficial.

System Description. The augmented spark, resonance, and combustion-wave ignition systems as applied to AMPS aerospike are described briefly in the following paragraphs.

Augmented Spark. Augmented spark ignition (Fig. 8) has proven its reliability in the J-2 and RL-10 O_2/H_2 engines. The configuration used in these systems, however, would be excessively heavy in the AMPS application where 24 separage ignition sources are required. The compact, integrated spark exciter/plug unit (Fig. 4) developed for Space Shuttle Auxiliary Propulsion is better suited to the AMPS engine. However, even advanced units are potentially heavy because:

1. Twenty-four integrated exciter/plug units are required; current studies indicate that these units weigh slightly less than 1 pound each.
2. A central exciter with individual plugs requires more than 50 feet of shielded, evacuated cable (which negates much of the weight saving of the reduced number of exciters and aggravates the potential radio interference problem).

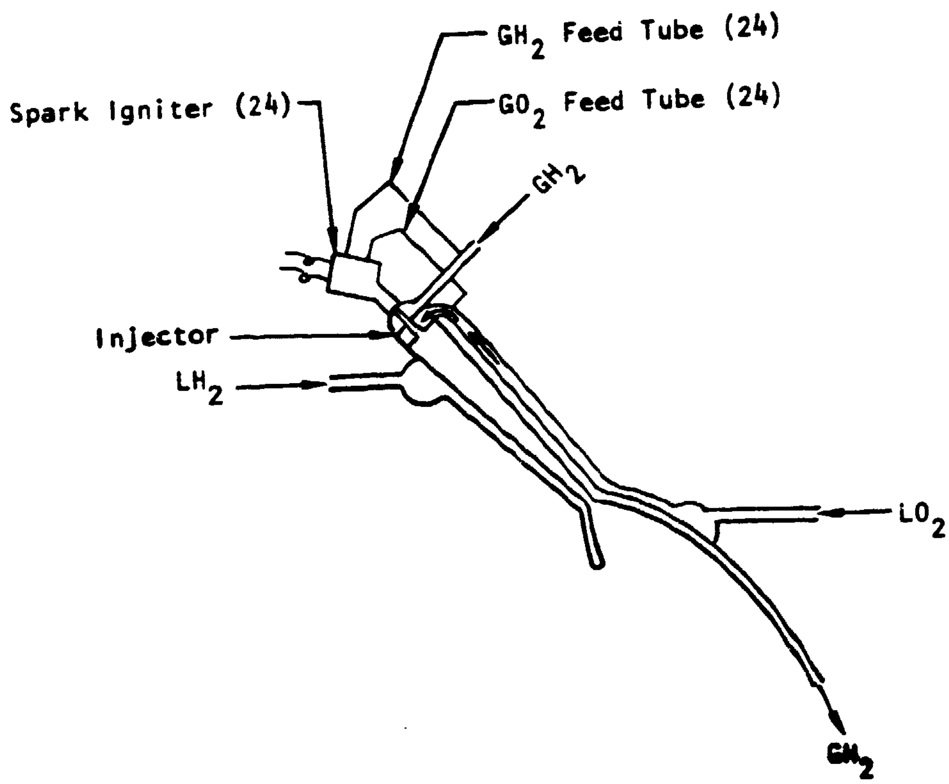

Figure 8. Spark Igniter

Resonance Igniter. Two versions of the resonance igniter approach were evaluated. The first, shown in Fig. 9, employs an oxidizer and fuel control valve at each of the 24 segments (opposed fuel and oxidizer flow method). This configuration provides the highest degree of similarity between the behavior of individual igniters, i.e., the priming lengths and volumes are small and are identical for all 24 segments. This precludes the possible need for matching line resistances as may be required in the centrally controlled resonance igniter system (premixed fuel and oxidizer flow method) shown in Fig. 10. The matching problem is expected to be minimal, however, and the weight saving achieved by employing one set of valves rather than 24 justifies the selection of the single-control configuration. In either system, a 0.008-lb/sec (3.63 gr/sec) nominal flowrate (at MR = 1) is required. Since this flow amounts to less than one-half of 1 percent of the total flow and mixes with the main injector flow, the igniter has no effect on engine performance.

Although resonance ignition is not currently in use in operational rocket engines, the feasibility and reliability of resonance igniters have been demonstrated in technology programs conducted in support of Space Shuttle Auxiliary Propulsion development (see Ref. 2). The experience gained in these efforts is directly applicable to the start-tank fed designs since the propellant flowrates, pressures, and temperatures during AMPS engine ignition are comparable to those tested.

An essential question to be resolved prior to a final selection is whether a reliable resonance igniter can be designed to operate using the propellants initially delivered to the thrust chamber under tank head. Although resonance O_2/H_2 ignition with low-pressure propellants has been demonstrated (Ref. 2) the short time delays required in a rocket engine must still be confirmed. With tank-head feed, the resonance igniter would achieve the schematic simplicity of the spark system, would be less complex, would have no radio frequency interference problems, and would be lighter.

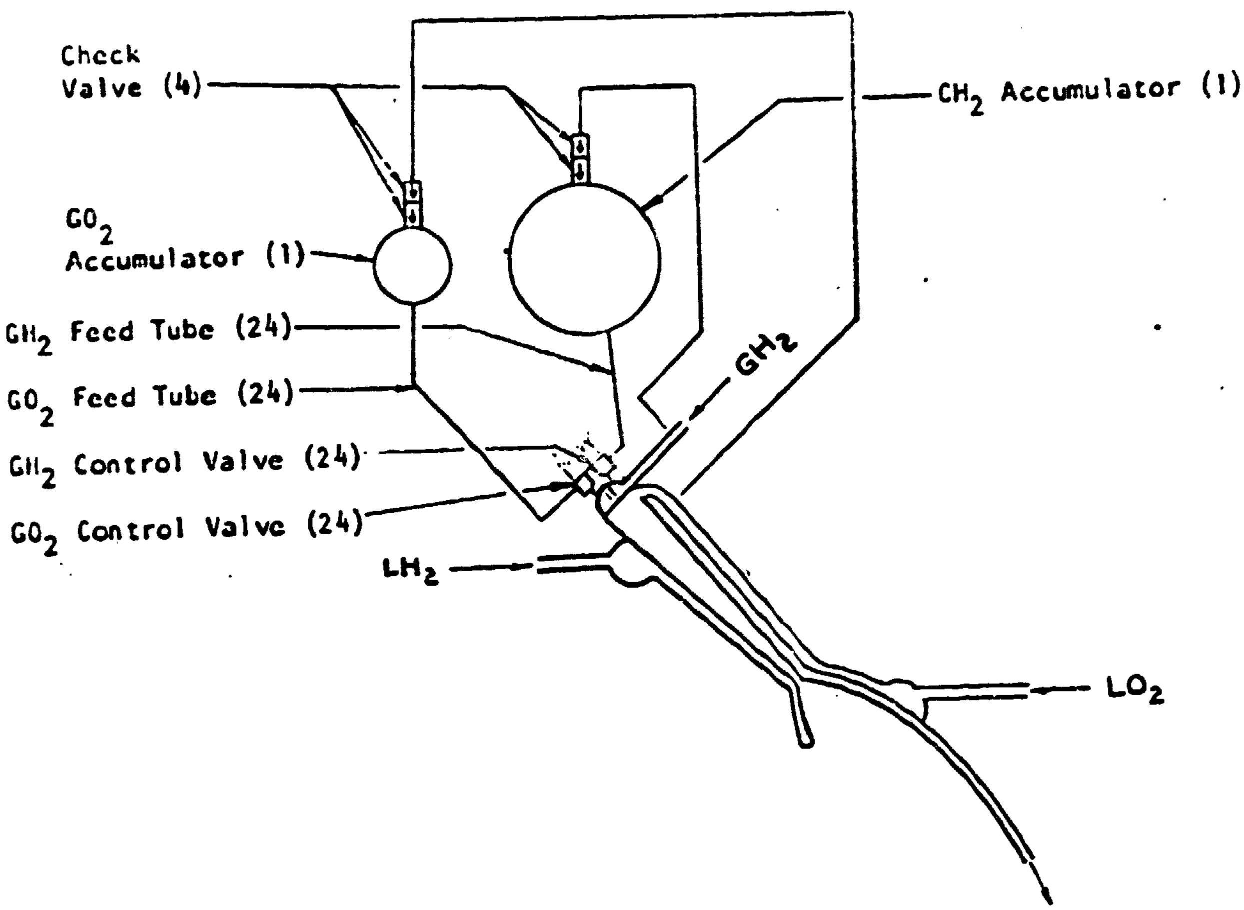

Figure 9. Resonance Igniter, Separate Segment Control, Opposed Fuel and Oxidizer Flow

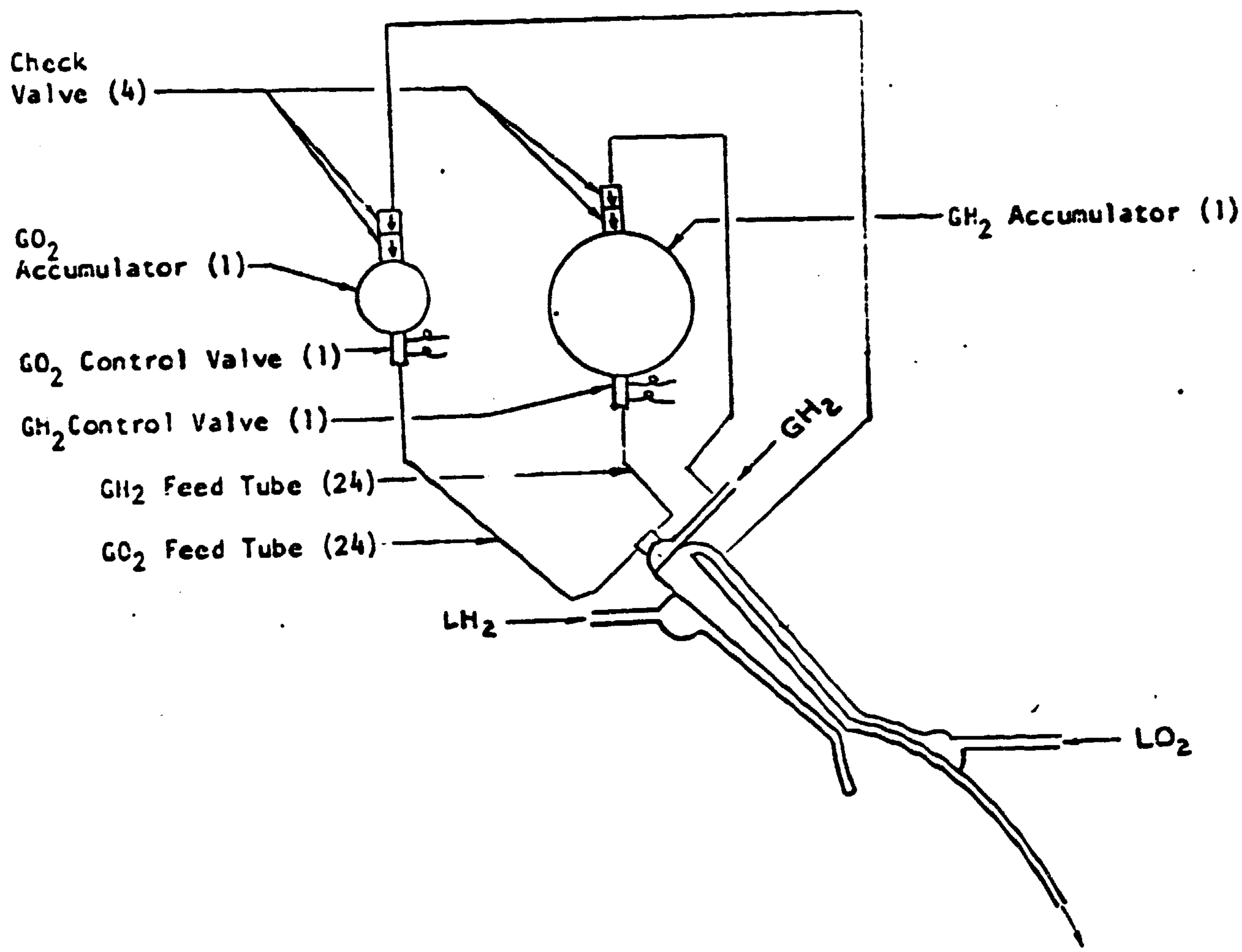

Figure 10. Resonance Igniter, Premixed Fuel and Oxidizer Method

Combustion Wave. The combustion wave ignition system (Fig. 11) employs a technique demonstrated in a recent experimental program. The concept is based upon the fact that combustion can be initiated at a central location and will travel rapidly through any path(s) primed with a combustible mixture. Though flame temperatures are high, the combustion process moves so rapidly along the path that the heating at any point is not sufficient to overheat the hardware.

The concept offers a promising way to construct a lightweight, multiple-ignition source system, and has been developed sufficiently to warrant its use in the nominal AMPS engine design. Limits on the ability of a combustion wave to ignite an O_2/H_2 stream have been defined, and sequencing to achieve a quasicontinuous ignition source has been demonstrated.

AMPS Ignition Study - Conclusions

Since detailed designs of each of the candidate systems were not prepared during the ignition system study, the comparison was based upon a review of the schematics shown previously and upon estimates of component weights.

In the resonance ignition, and the combustion wave systems, rechargeable tankage sufficient for 1 second of operation was assumed. Start tank volume was governed by the case in which recharging occurs during a minimum-thrust firing, and start tank pressure was governed by the case in which recharging occurs during a full-thrust firing.

Two alternative techniques were evaluated: tank blowdown and regulated, uniform discharge. Based on the assumptions stated in Table 5, the weights for each system were close to equal with the regulator weight equaling the tank weight differences for the two systems. As shown in Fig. 12, the blowdown tanks provide 1 second of operation when charged initially to 200 psi (138 N/cm^2). For an initial charge pressure of 1200 psia (828 N/cm^2), the ignition source is adequate (i.e., $\dot{w}_{total}$ > 0.006 lb/sec) for 3.4 seconds.

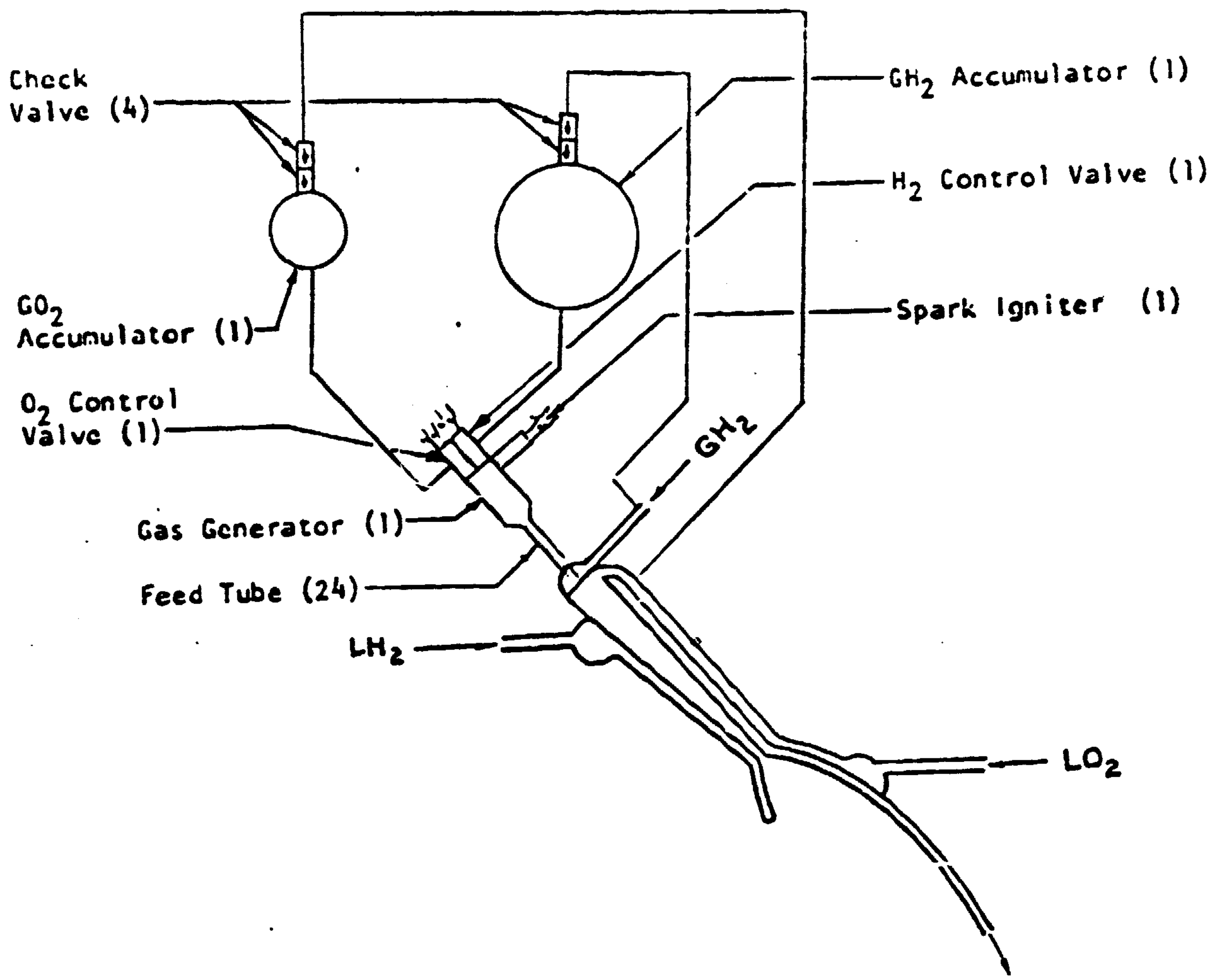

Figure 11. Combustion Wave Igniter

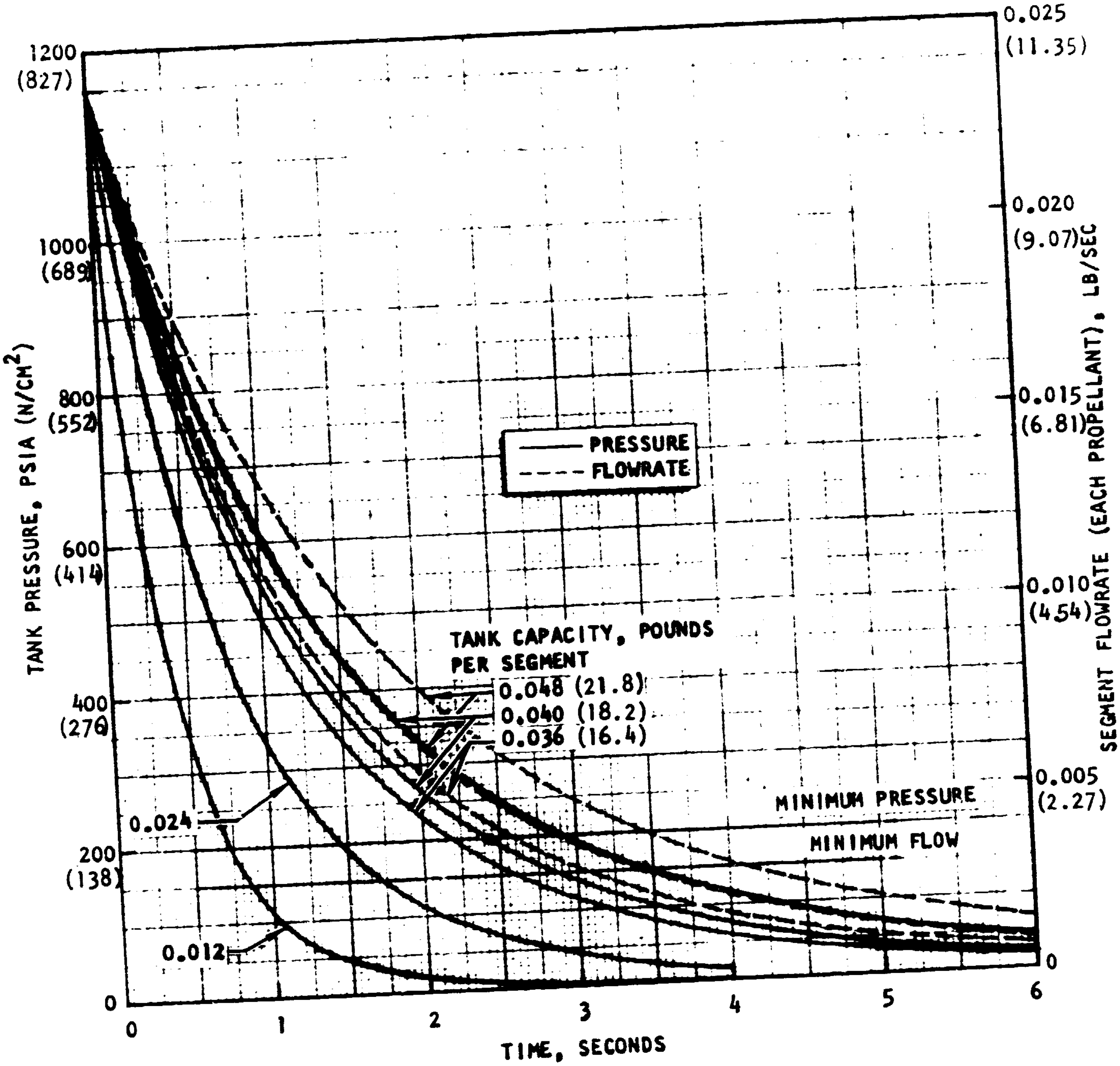

Figure 12. Igniter Propellant Accumulator Blowdown Characteristics

TABLE 5. ASSUMPTIONS FOR TANK WEIGHT ESTIMATES

Gas Storage Pressure, psia	200 (min); 1200 (max)
Gas Storage Temperature, R	600 (GH_2); 340 (O_2)
Gas Flowrate (total at MR = 1), lb/sec	0.006 (min); 0.008 (nom)
Tank Material	
Yield Stress, psi	100,000
Safety Factor	1.5
Density, lb/in.^{3}	0.28
Igniter Operation Duration, seconds	1.0 (min)

Based on the previously stated ground rules, the final selection of the ignition system for the AMPS aerospike engine was influenced primarily by the following criteria: (1) technology status, (2) design complexity, and (3) ignition system weight.

As a result of this study, the combustion wave ignition system was recommended for the AMPT aerospike engine. A weight comparison of the candidate ignition system is shown in Table 6. The weight of the combustion wave system with storage bottles is comparable to a resonance system or a redundant spark ignition system. The spark system poses the greatest problems with respect to integration into the thrust chamber/injector assembly for the AMPT aerospike application. Because of this design complexity and its heavier weight, the ASI system was eliminated. The technology status of resonance igniters has not been advanced to the extent of that of combustion wave systems, and they were eliminated for this reason. Combustion wave ignition was selected because of the following reasons: (1) it is easily integrated into the thrust chamber assembly, (2) the possibility of utilizing tank-head-supplied igniter flows results in significantly lower weight than the other systems, and (3) operation at ignition and mainstage conditions applicable to the AMPT aerospike engine has been demonstrated.

TABLE 6. AMPT IGNITION SYSTEM SUMMARY

Resonance Igniter Systems - Tank Blowdown: Single Valves	Weight, pounds	Resonance Igniter Systems - Tank Blowdown: Separate Valves	Weight, pounds	Combustion Wave System	Weight, pounds	Spark Ignition System	Weight, pounds
Inlet Check Valves, Oxidizer (2)	0.5	Inlet Check Valves, Oxidizer (2)	0.5	Inlet Check Valves, Oxidizer (2)	0.5	Spark Igniters	24.0
Inlet Check Valves, Fuel (2)	0.5	Inlet Check Valves, Fuel (2)	0.5	Inlet Check Valves, Fuel (2)	0.5	Wiring (24)	1.5
Tank, Oxidizer	2.5	Tank, Oxidizer	2.5	Tank, Oxidizer	2.5	Tank, Oxidizer	2.5
Tank, Fuel	30.4	Tank, Fuel	30.4	Tank, Fuel	30.4	Tank, Fuel	30.4
Discharge Valve, Oxidizer	0.5	Resonator Inlet Valves, Oxidizer (24)	6.0	Discharge Valve, Oxidizer	0.5	Discharge Valve, Oxidizer	0.5
Discharge Valve, Fuel	0.5	Resonator Inlet Valves, Fuel (24)	6.0	Discharge Valve, Fuel	0.5	Discharge Valve, Fuel	0.5
Resonators (24)	6.0	Resonators (24)	6.0	Gas Generator	0.5		
				Spark Igniters (2)	2.0		
	40.9		51.9		37.4		59.4

*For regulated system, oxidizer and fuel tanks are 18.5 and 0.5 pounds, respectively. Since two regulators total 14 pounds, blowdown and regulated system weights are nearly identical

MONOPROPELLANT RESONANCE IGNITION

A brief investigation of the application of resonance ignition for monopropellant engines were performed. Two hydrazine-pulsed propulsion systems were specified for the investigation by the JPL Technical Manager. The duty cycle requirements for these two propulsion systems were as follows:

1. Direct Attitude Control System:
   0.01 second thrust on
   30 minutes thrust off
2. Momentum Wheel:
   0.01 second thrust on
   0.9 second thrust off
   30 pulses in 30 minutes
   Duty cycle to be repeated every 3 to 4 hours

It was also specified that both of the above engines had to have a thrust of 0.1 lbf (0.448 N), and required a N_2H_4 flowrate of $5x10^{-4}$ lb/sec ($2.275x10^{-4}$ Kg/sec).

Direct Attitude Control System

In order to decompose N_2H_4, any of the resonance ignition methods discussed previously would have to achieve a temperature level of 1160 R (645 K) (assumed minimum N_2H_4 temperature in this study). Even with low molecular weight gases such as helium or hydrogen, the time required to reach 1160 R (645 K) at the closed end of a well-insulated resonance cavity is of the order of 0.01 second. Since the specified duty cycle requires that the thrust ON time be 0.010 second, it would appear that resonance ignition for this system is not applicable.

Momentum Wheel

Two resonance methods were considered for application to the Momentum Wheel Propulsion System: (1) generation of a 1160 R (645 K) surface at the tip of the resonance cavity and impinging liquid N_2H_4 on this surface, and (2) atomizing the

liquid N_2H_4 with pressurized helium prior to injection into a closed-end resonance cavity. Both of these methods present a drawback in that a stored gas would have to be expended, thus in effect, adding to the propellant weight. In the case of the hot-surface ignition, the resonating gas would have to be thrown overboard and thrust cancellation of this gas would have to be considered. Based on the experience of the premixed O_2/H_2 resonance igniter development, the time required for ignition of atomized N_2H_4 in helium would be in excess of 0.1 second.

In view of these above considerations in addition to the stringent duty cycle requirements and demands on fuel economy, here again, it appears that the resonance ignition concept would not be applicable to Momentum Wheel propulsion system.

TASK II - EXPERIMENTAL STUDY

INTRODUCTION AND BACKGROUND

For most oxygen/hydrogen propulsion systems, the propellants are stored at cryogenic conditions. If the resonance igniter were selected, a gas conditioner would have to be incorporated as part of the propellant feed system. To reduce the gas conditioner requirements (for minimum size), the resonance igniter would have to be designed to operate with low inlet propellant temperatures of the order of 200 R (111 K).

The geometrical configuration and performance characterization of a resonance igniter is most readily determined experimentally. A two-phase approach to the development of a resonance ignition system was successfully used during a previous Rocketdyne effort (Ref. 2) for application to the Space Shuttle auxiliary propulsion system (SS/APS). This approach was basically duplicated during the present program.

During the first phase of the test program, the geometry of the resonance igniter is determined using the lead gas only (hydrogen). For a given resonance cavity, the gas temperature, at the end of the cavity, is measured as a function of time while the critical parameters (gap distance and restriction diameter) are varied systematically. These tests are carried out until the optimum igniter geometry is achieved, i.e, when a particular igniter geometry results in the maximum gas temperature for a given flow duration.

Keeping the "optimized" igniter configuration fixed, the second phase of the development program consists of testing with both propellants (oxygen and hydrogen). During these tests the ignition characteristics and the operational envelope of the igniter are determined.

During the SS/APS resonance igniter investigation (Ref. 2) the following facts were indicated:

1. The resonance igniter geometrical configuration was optimized using ambient-temperature hydrogen
2. With conditioned hydrogen flowing into the optimized configuration, heating characteristics did not behave according to expected trends
3. With the configuration optimized for ambient conditions, reduced ignition reliability and longer ignition delays resulted when both oxygen and hydrogen propellants were at temperatures below ambient.

These facts formed the basis for the Task II program. In the following paragraphs, results of the ambient- and low-temperature propellant tests as performed during the effort described in Ref. 2, will be summarized. These results will specifically point out the former problem areas and the reasons for the experimental program conducted during this contract.

Results of SS/APS Geometry Optimization Tests

The purpose of this test phase was to determine the geometry of the resonance igniter that would result in a hydrogen temperature of 1460 R (811 K) within a minimum time from start of flow. The criterion of achieving a hydrogen temperature of 1460 R (811 K) was chosen on the basis of past O_2/H_2 combustion research, which indicates that this temperature is sufficient to cause ignition over a broad range of mixture ratios and propellant inlet pressures.

The rate at which a gas is heated in a resonance configuration is primarily dependent upon the proper relation between the following geometrical parameters:

1. Gap distance between the feed nozzle and the inlet to the resonance cavity
2. Restriction nozzle throat diameter
3. Resonance cavity configuration

The tests were performed with a variable geometry apparatus (Fig. 13) to conveniently modify the three parameters mentioned above. All of the geometry optimization tests (also referred to as heating tests) were run with ambient hydrogen only, at a nominal flowrate of 01020 lb/sec (91 gr/sec), and total inlet pressure of 375 psia (259 N/cm^2). A thermocouple was located at the closed end of the resonance cavity to monitor the hydrogen temperature history. The restriction orifice was varied by means of a remote controlled hydraulic valve. Two different resonance tubes made out of quartz to prevent heat losses, shown in Fig. 14, were fabricated and tested. The dimensions of the step-tapered cavity configurations were based on the results of previous research. With one of the resonance tubes placed in the variable geometry hardware, the test procedure was as follows: the gap distance and the restriction opening were set at particular values, the hydrogen valve was opened, and the resonance temperature (along with other pertinent flow variables) was recorded as a function of time. Tests were made in a similar manner with different values of restriction openings until the optimum restriction opening was found. The entire procedure was repeated with different gap distances, again, until the optimum gas distance was found.

For each of the resonance tubes tested (Configurations I and II, shown in Fig. 14) the hydrogen resonance temperature as a function of time was optimized for gap and restriction settings. With Configuration I, starting with ambient-temperature hydrogen at 375 psia (259 N/cm^2) stagnation pressure, the hydrogen resonance temperature reached 1460 R (811 K) in 27 milliseconds from the time the hydrogen valve was opened. With hydrogen at similar inlet conditions, Configuration II reached 1460 R (811 K) in 41 milliseconds. Configuration I was chosen for the subsequent combustion tests. It should be noted that the time periods quoted were as measured by the thermocouple response and therefore included the inherent thermocouple lag, i.e., actual gas temperatures during transient are considerably higher. This was borne out during subsequent oxygen/hydrogen combustion tests where ignition occurred when the oxidizer valve was opened 3 milliseconds after opening of the fuel valve.

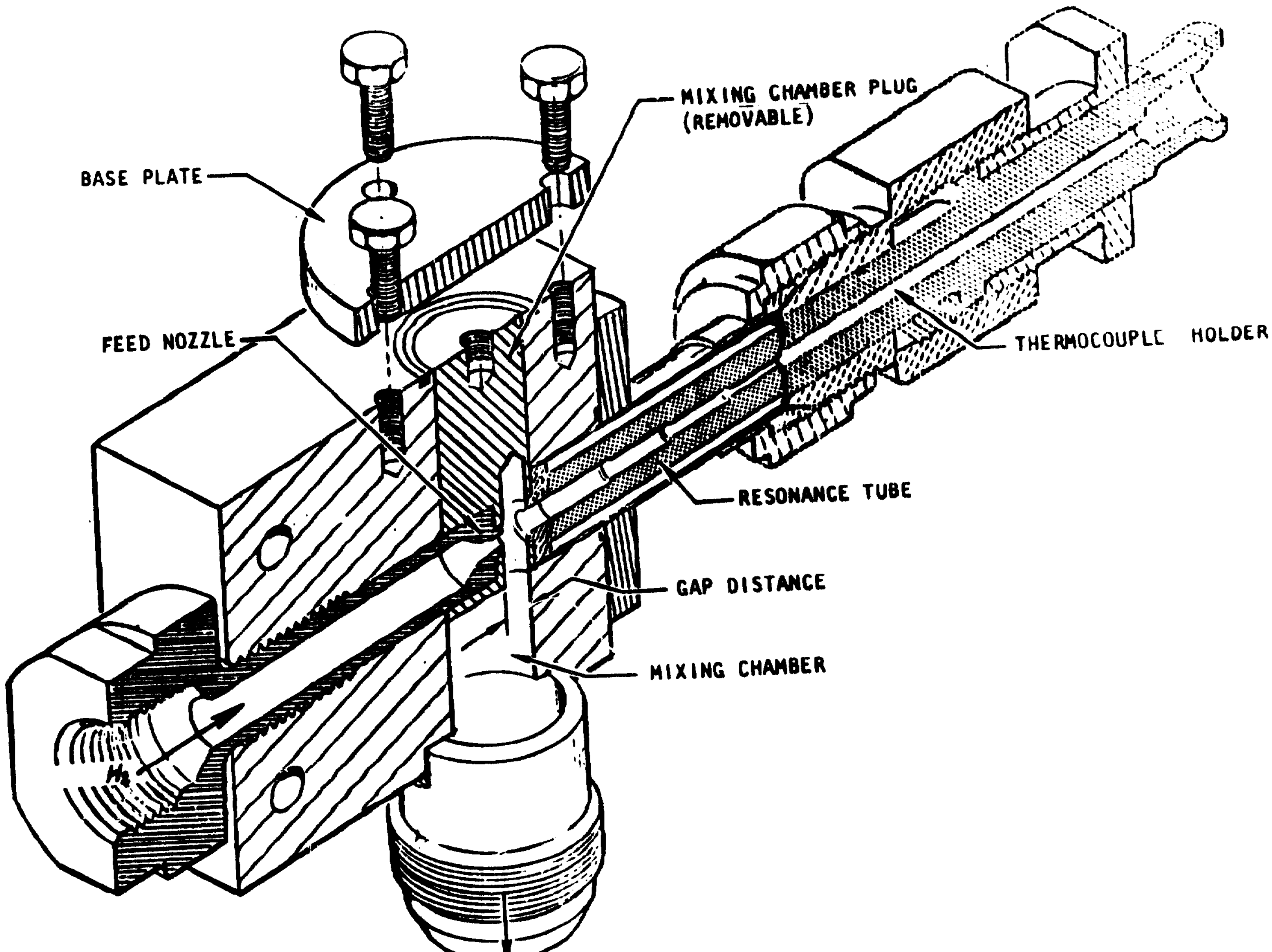

Figure 13. Variable-Geometry Test Hardware

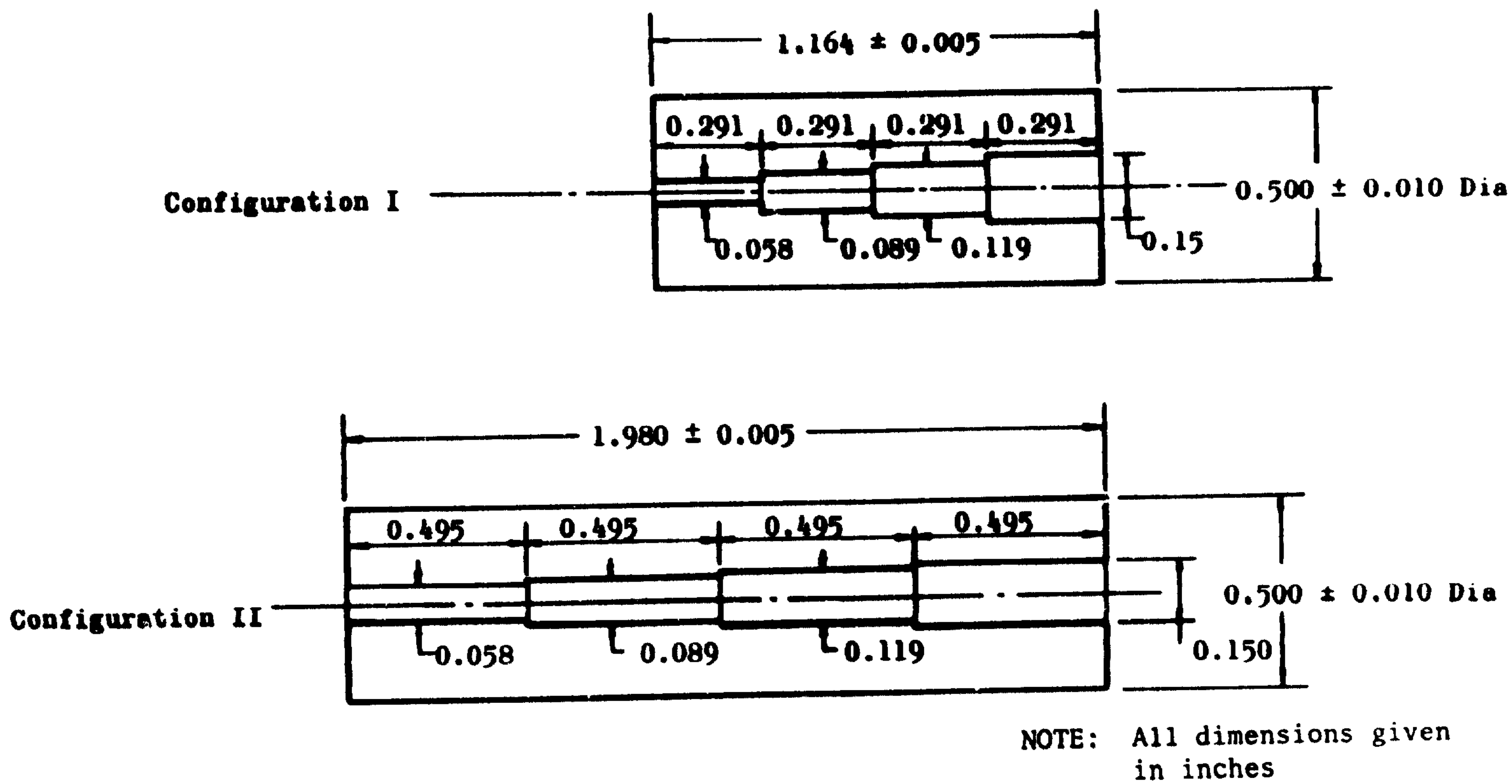

Figure 14. Resonance Tube Configurations

The conditioned hydrogen tests, to be discussed in the next section, were conducted with the Configuration II resonance tube.

Results of SS/APS Conditioned Hydrogen Tests

A series of tests was made to find the resonance temperature-time relation for hydrogen inlet total temperatures other than ambient. A heat exchanger (using nitrogen as the heat transfer medium) was placed ahead of the hydrogen inlet valve and the hydrogen total temperature was varied between 220^{o} R (125^{o}K) and 785 R (436 K). The resonance tube Configuration II and the fixed optimum gap were used throughout this test series. The major variables were the hydrogen total temperature and the restriction area (as set by a remotely controlled hydraulic valve). Figure 15 shows a typical plot of the measured resonance temperature as a function of time for hydrogen total temperatures of 330 R (183 K), with parametric variations of steady-state pressure ratio (P_T/P_{MC}). On these plots, the initial time (t = 0) is taken from the instant a pressure rise is indicated in the mixing chamber. Close examination of the data indicates that the initial temperature readings remain near ambient for a short time period. The main reason for this occurrence is due to difficulties in temperature conditioning of the hardware, especially in the region of the closed-end resonance cavity where the thermocouple is located.

Figure 16 indicates the highest measured resonance temperatures as a function of the inlet hydrogen total temperature for two different time slices (50 and 100 milliseconds) after start of hydrogen flow. It should be re-emphasized that the points shown in Fig. 16 were obtained with a resonance igniter having a fixed gap and a single resonance tube configuration, and that the resonance temperatures indicated are for optimum pressure ratios (P_T/P_{MC}), which are different for each particular inlet hydrogen total temperature.

The resonance temperatures obtained with ambient inlet hydrogen total temperature (i.e., passing hydrogen through the heat exchanger without heating or cooling) appear to be out of line with the rest of the points obtained with temperature-conditioned hydrogen. The principal reason for this deviation can be attributed

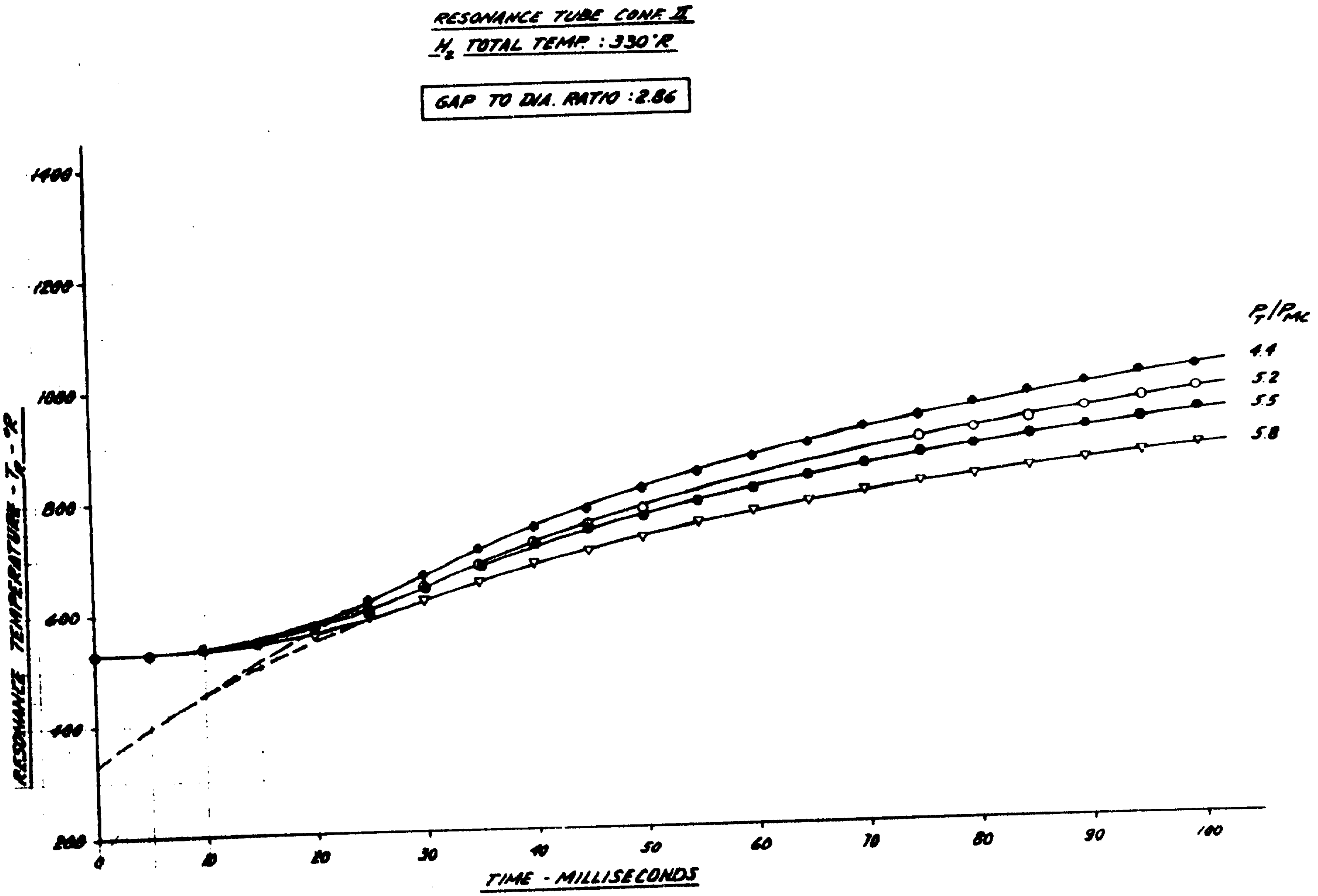

Figure 15. Resonance Temperature vs Time

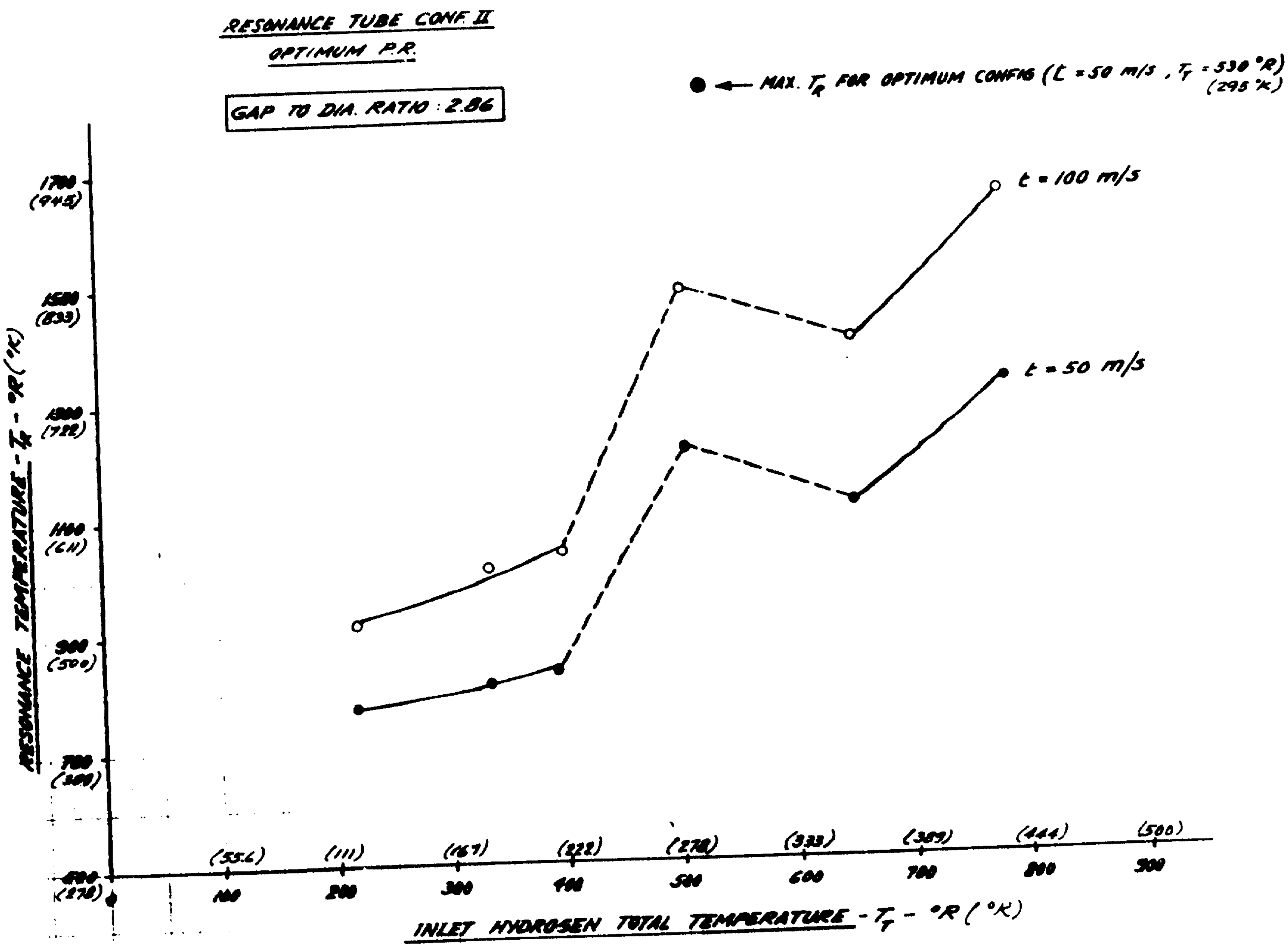

Figure 16. Temperature vs H_2 Inlet Temperature

to the fact that the fixed-gap and resonance-cavity configuration used for this test series was optimized during the resonance igniter geometry optimization test phase using ambient hydrogen. Thus, data in Fig. 16 strongly suggest that both the gap and the resonance-cavity configuration should be re-optimized for the lowest inlet hydrogen total temperature at which the resonance igniter is expected to run.

TASK II - GEOMETRY OPTIMIZATION INVESTIGATION

Igniter Configuration

All tests were performed in the Thermodynamics Laboratory located at the B-1 Division (see Appendix A for facility description) using the hardware shown in Fig. 13. As stated previously, this hardware provided the flexibility for easily modifying the critical geometrical parameters of the igniter. Two different resonance cavities were tested (Fig. 17). The heating characteristics of one of these cavities

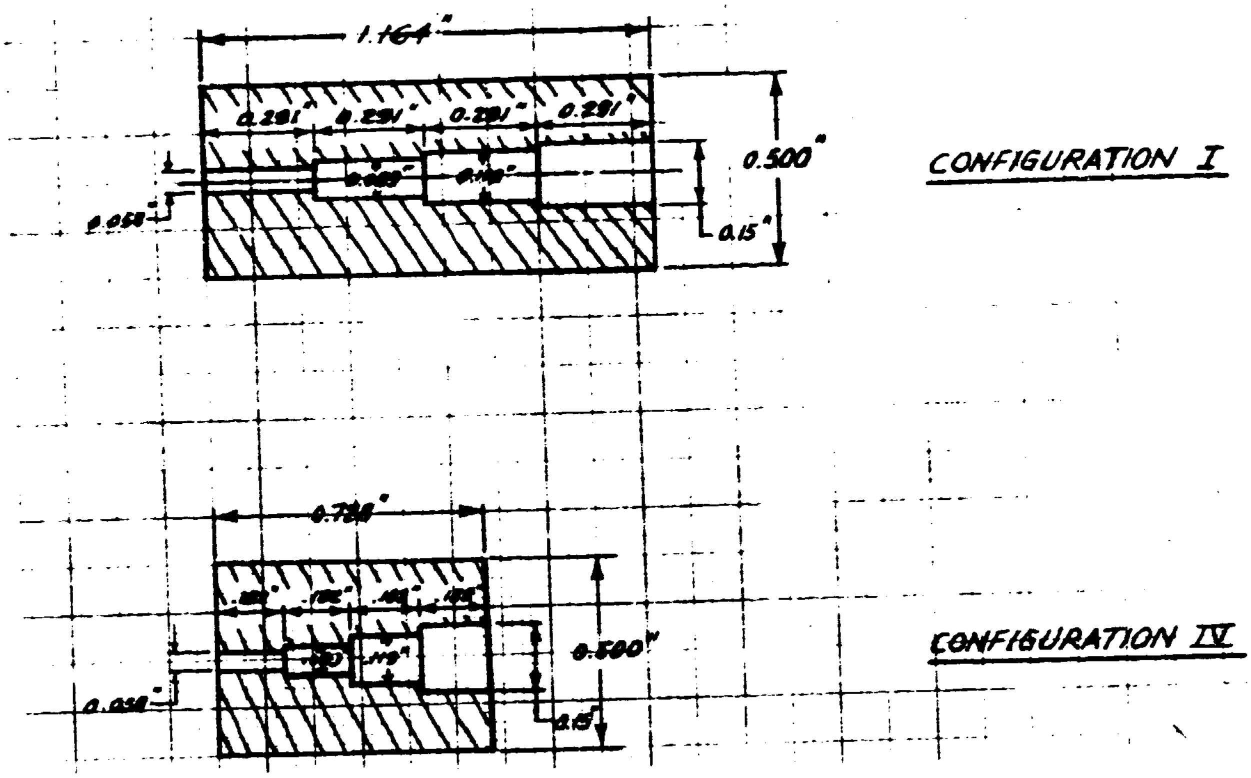

Figure 17. Resonance Cavity Configurations

(Configuration I) were investigated in a previous effort (Ref. 2) using only ambient-temperature hydrogen. Since one of the aims of the programs was to increase the igniter performance, it was felt that the cavity geometry should be redesigned for low hydrogen temperature operation. The design of Configuration IV (Fig. 17) was arrived at by assuming that the resonance frequency of both Configuration I and IV be the same. The resonance frequency is given by the following equation (Ref. 6):

$$f = \frac{c}{4L}$$

where

c = speed of sound

L = length of the resonance cavity

Therefore, to keep the frequency a constant while operating at two different temperature levels (530 R/295 K) and 200 R/111 K) the length ratio of the two cavities is:

$$\frac{L_I}{L_{IV}} = \sqrt{\frac{(\gamma T)_I}{(\gamma T)_{IV}}} = \sqrt{\frac{1.4x530}{1.46x200}} = 1.594$$

The step length of 0.291 in. (0.739 cm) for Configuration I thus becomes 0.182 (0.462 cm) for Configuration IV.

Test Program

The two cavity configurations shown in Fig. 17 were tested with hydrogen only and resonance temperatures were measured as functions of time while varying the gap distance and pressure ratio (ratio of hydrogen inlet total pressure to mixing chamber pressure, P_T/P_{MC}). Again, for both cavity configurations, two hydrogen total temperatures were used: (1) ambient total temperature of approximately 530 R (294 K), and (2) low total temperatures ranging from 200 (111) to 250 R (139 K) (hydrogen being cooled in a liquid nitrogen heat exchanger). For a

particular test, the gap distance was set to a specified dimension by adjusting the position of the hydrogen feed nozzle, and the pressure ratio was varied by opening or closing a remote-controlled Annin valve. The total pressure of the hydrogen flowing into the resonance igniter was maintained at approximately 375 psia (258 N/cm^2). The resonance temperature was measured by a thermocouple placed at the end of the resonance tube, thus effectively sealing the end of the smallest cavity diameter. Temperature increases were recorded as soon as the hydrogen inlet valve was opened.

Ninety-four tests (see Tables 7 and 8) were performed in the manner just described in order to determine: (1) which of the two cavity configurations resulted in the highest resonance temperature during finite hydrogen flow time, and (2) the optimum gap dimension and the pressure ratio which resulted in the highest resonance temperature.

Data Analysis

Figures 18 and 19 give the results of the tests conducted with the Configuration I resonance cavity using ambient-temperature hydrogen. Figure 18 shows the resonance temperature as a function of pressure ratio (P_T/P_{MC}) with parametric variations of gap distance. The resonance temperature indicated is taken at a time slice 50 milliseconds after the opening of the hydrogen valve closest to the resonance igniter. Figure 19 is a similar plot except that the resonance temperature is taken 100 milliseconds after the opening of the hydrogen valve. Both Fig. 18 and 19 check out the findings of the previous experiments reported in Ref. 2, namely, that (1) a gap of 0.394 in. (1.0 cm) results in the maximum resonance temperature in the time periods of 0 to 100 milliseconds of ambient temperature hydrogen flow, and (2) the maximum resonance temperature can be achieved over a relatively wide range of pressure ratios (5.6 to 6.8).

Figure 20 shows the test results when using low-temperature hydrogen (200 to 240 R (111 to 133 K). From Fig. 20 it can be seen that for the gap distances tested at the highest resonance temperature was achieved with a gap of 0.340 in. (0.863 cm) at a pressure ratio of 6.1. These tests confirm the expectation that the use of

TABLE 7. GEOMETRY OPTIMIZATION TEST DATA

Test Number	T_{H_2} Inlet K	T_R at 50 ms K	T_R at 100 ms K	$P_T/P_{M.C.}$	Gap m × 10^{-2}
1	294	545	675	6.15	1.17
2		574	649	5.65	
3		523	626	5.25	
4		632	754	6.6	
5		592	704	6.07	1.24
6		506	617	5.7	
7		494	539	5.25	
8		538	631	5.97	
9		602	780	6.78	1.00
10		711	821	6.4	
11		524	792	6.1	
12		681	824	5.87	
13		687	817	5.76	
14		706	803	5.5	
15		692	747	5.37	
16		641	691	5.12	
17		618	742	6.7	0.87
18		646	770	6.1	
19		647	776	5.7	
20		684	815	5.32	
21		652	805	4.84	
22		591	--	4.37	

TABLE 7. (Concluded)

Test Number	T_{H_2} Inlet K	T_R at 50 ms K	T_R at 100 ms K	$P_T/P_{M.C.}$	Gap $m \cdot 10^{-2}$
23	117	350	419	7.3	0.86
24	122	329	426	7.23	
25	128	383	456	7.0	
26	134	390	464	6.85	
27	136	425	562	6.1	
28	136	445	522	5.65	
29	139	398	448	5.25	
30	142	304	314	4.75	
31	117	383	430	7.15	0.94
32	119	380	435	7.0	
33	134	398	458	6.1	
34	136	382	470	5.75	
35	136	336	366	5.30	
36	114	374	420	7.15	1.04
37	122	383	427	6.5	
38	125	351	397	6.1	
39	125	337	367	5.65	
40	119	367	411	7.25	1.14
41	122	354	400	6.5	
42	128	348	395	6.1	
43	133	353	403	5.7	
44	136	284	299	5.2	
45	114	328	362	7.2	0.64
46	122	338	386	6.1	
47	128	337	394	5.7	
48	133	356	415	517	
49	117	412	463	4.65	
50	117	316	360	4.3	

NOTES: 1) All tests conducted with Resonance Tube Configuration I
2) Inlet hydrogen pressure approximately 0.0259 N/m^2

TABLE 8. GEOMETRY OPTIMIZATION TEST DATA

Test Number	T_{H_2} Inlet K	T_R at 50 ms K	T_R at 100 ms K	$P_T/P_{M.C.}$	Gap [illegible]
1	294	533	662	6.[illegible]5	[illegible]
2		562	641	5.7	
3		572	657	5.33	
4		587	642	4.85	
5		542	611	6.67	1.07
6		611	647	6.15	
7		595	709	5.3	
8		550	637	4.85	
9		449	426	4.35	
10		556	647	6.7	0.91
11		566	648	6.1	
12		572	649	5.7	
13		591	680	5.25	
14		553	617	4.4	
15		549	649	6.65	0.84
16		581	668	6.05	
17		594	672	5.7	
18		607	683	5.3	
19		596	690	4.87	
20		575	629	4.4	
21		479	494	3.92	
22		612	674	6.7	0.76
23		607	658	6.1	
24		597	666	5.7	
25		575	682	5.3	
26		644	752	4.4	
27		499	506	3.96	

TABLE 8. (Concluded)

Test Number	T_{H_2} Inlet K	T_R at 50 ms K	T_R at 100 ms K	$P_T/P_{M.C.}$	Gap $m \times 10^{-2}$
28	--	--	367	6.15	0.86
29	--	--	436	5.8	
30	133	381	418	5.03	
31	131	360	382	4.5	
32	117	359	360	7.0	1.07
33	122	312	349	6.9	
34	128	356	400	5.8	
35	133	352	395	5.74	
36	136	338	377	6.6	
37	120	334	349	6.9	0.91
38	133	333	359	6.8	
39	128	371	417	5.82	
40	114	323	341	4.8	
41	145	311	347	5.9	0.84
42	145	301	345	5.38	
43	122	245	295	6.9	
44	128	246	258	6.13	

NOTES: 1. All tests conducted with Resonance Tube Configuration IV

2. Inlet hydrogen pressure approximately 0.0259 n/m^2

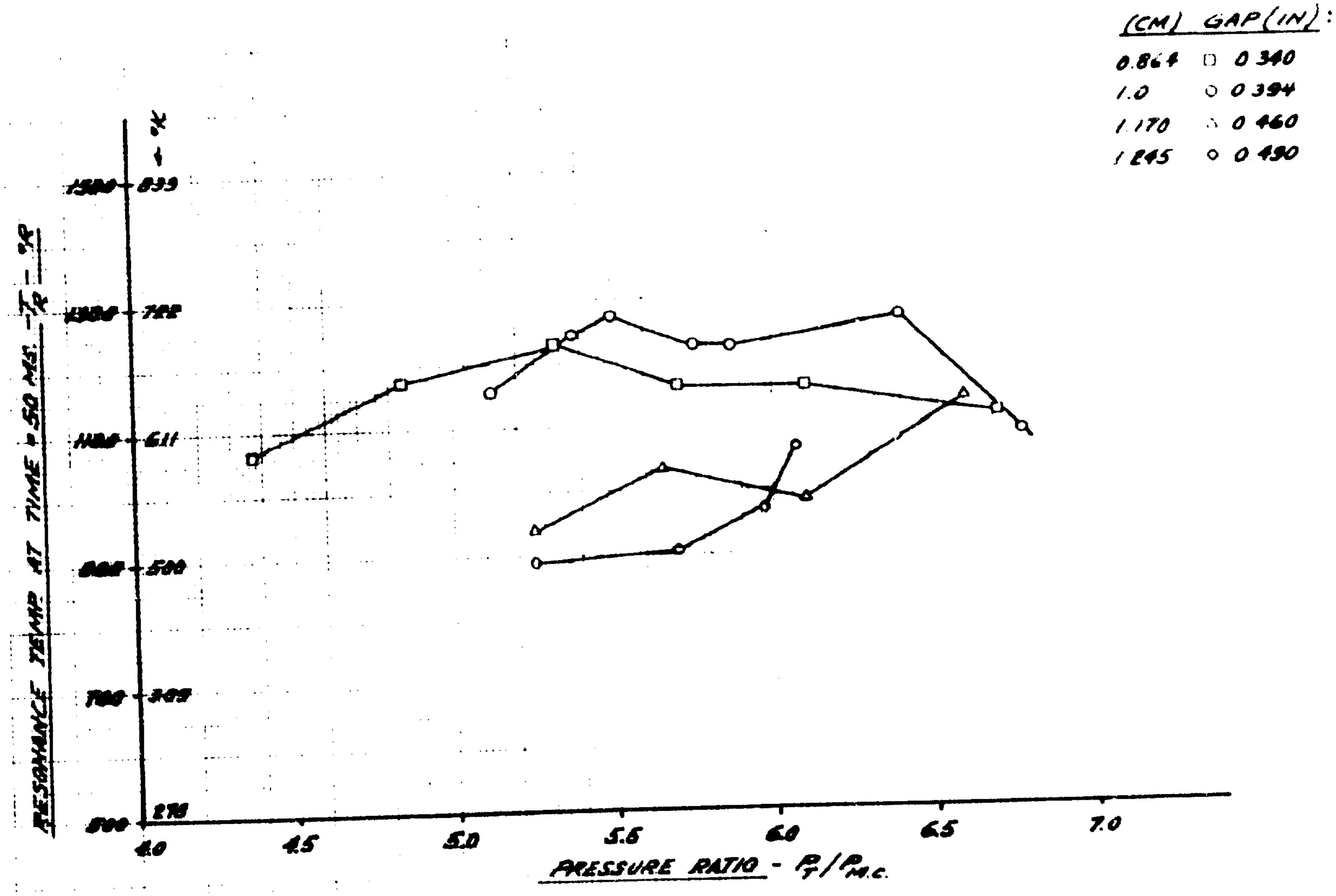

Figure 18. Resonance Igniter Geometry Optimization Resonance Tube Configuration I, Hydrogen Total Temperature Ambient (Time = 50 ms)

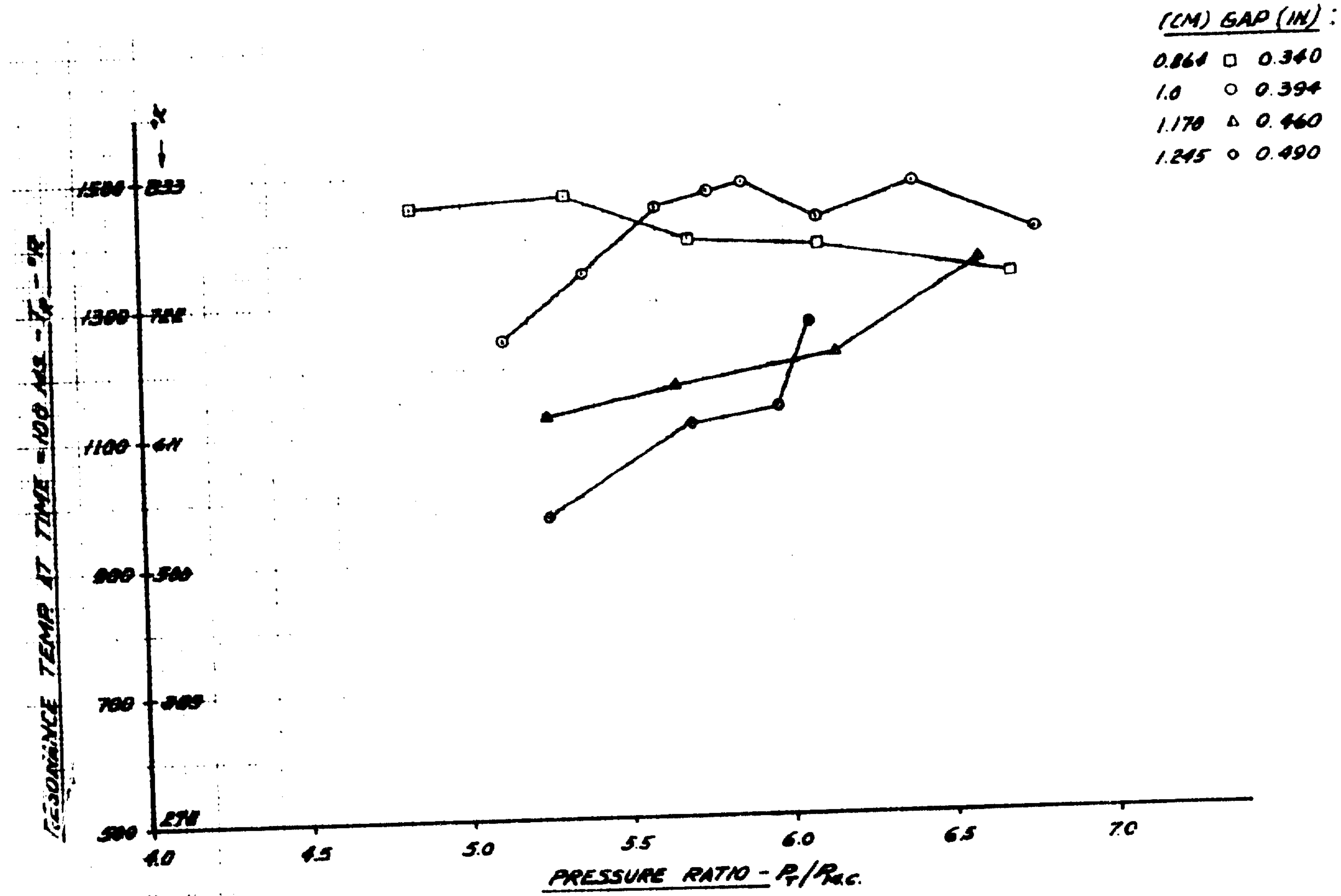

Figure 19. Resonance Igniter Geometry Optimization Resonance Tube Configuration I, Hydrogen Total Temperature Ambient (Time = 100 ms)

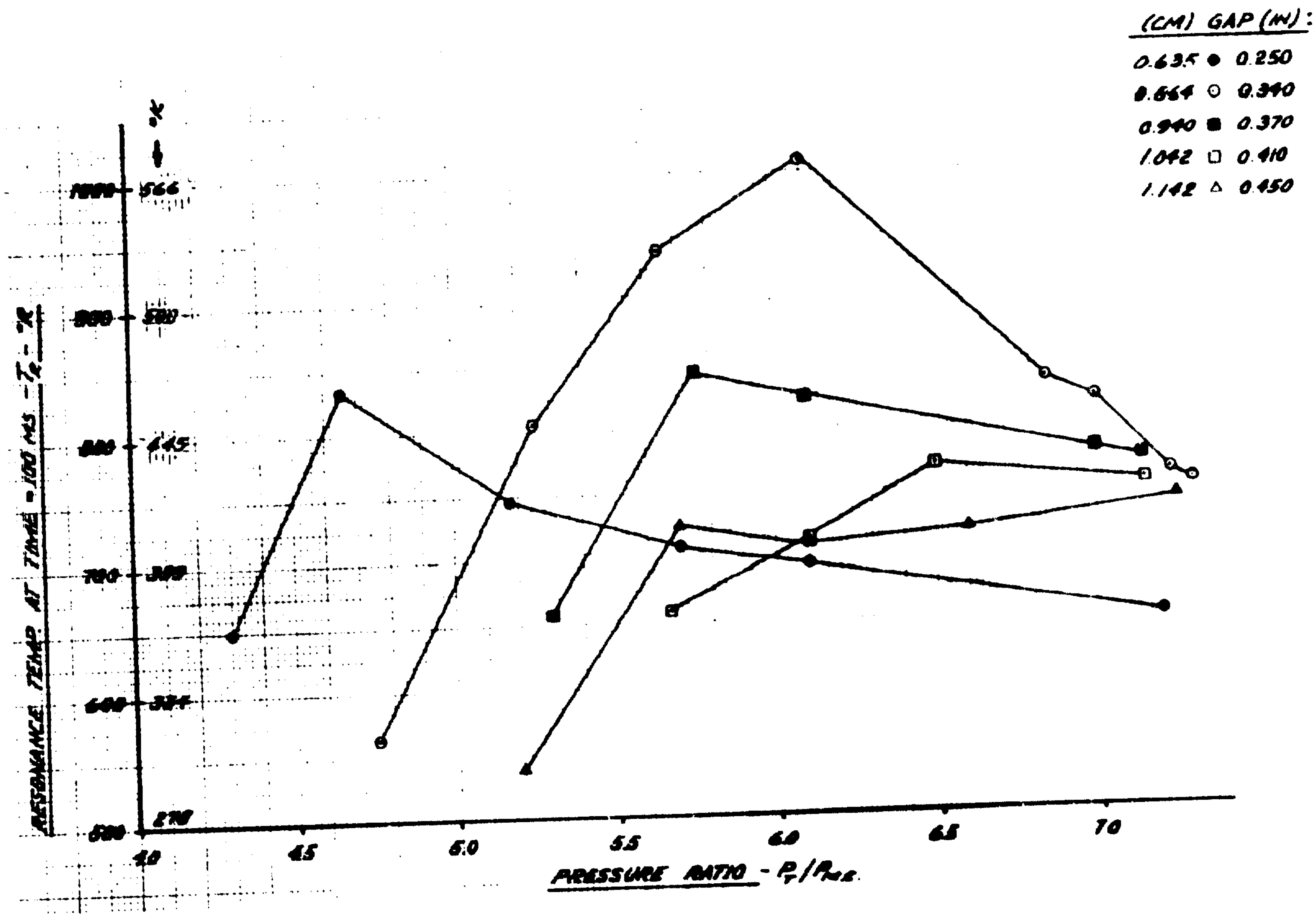

Figure 20. Resonance Igniter Geometry Optimization Resonance Tube Configuration I, Low Hydrogen Total Temperature (Pressure Ratio vs Resonance Temperature)

low-temperature hydrogen would influence the optimum resonance igniter configuration. Figure 20 also shows that for a given gap distance, the maximum resonance temperature is sensitive to pressure ratio, which is contrary to the results found during ambient-temperature hydrogen tests. Figure 21 is a cross plot of the results shown in Fig. 20 and shows the maximum resonance temperature after 100 milliseconds of hydrogen flow as a function of gap distance. Figure 21 indicates that the optimum gap distance in the region of 0.25 (0.635 cm) and 0.340 in. (0.863 cm) and the associated pressure ratio were not precisely determined during this phase of the test program.

Figures 22 and 23 show the results of the tests conducted with the Configuration IV resonance cavity. Figure 22 results are for the ambient-hydrogen tests, and Fig. 23 results are for the low-temperature hydrogen tests. All the test results indicate that the Configuration IV cavity leads to lower resonance temperature levels with either inlet hydrogen total temperatures when compared to the performance of the Configuration I cavity (see Fig. 18 and 19).

Summary of Geometry Optimization Test

1. Of the two resonance cavity geometries tested, use of the Configuration I cavity results in the highest hydrogen temperature increase for a finite hydrogen flow period.
2. With low hydrogen total temperatures the optimum gas distance and pressure ratio differ considerably from the values found during the tests with ambient-hydrogen total temperature.
3. When using low-temperature hydrogen, the maximum resonance temperature achieved with a fixed-gap distance is sensitive to pressure ratio.
4. A gap of 0.340 in. (0.863 cm) and pressure ratio of 6.1 resulted in the maximum resonance temperature with low-temperature hydrogen operation. To achieve a pressure ratio of 6.1 the restriction diameter of the igniter (fixed throat) will have to be 0.282 in. (0.721 cm).

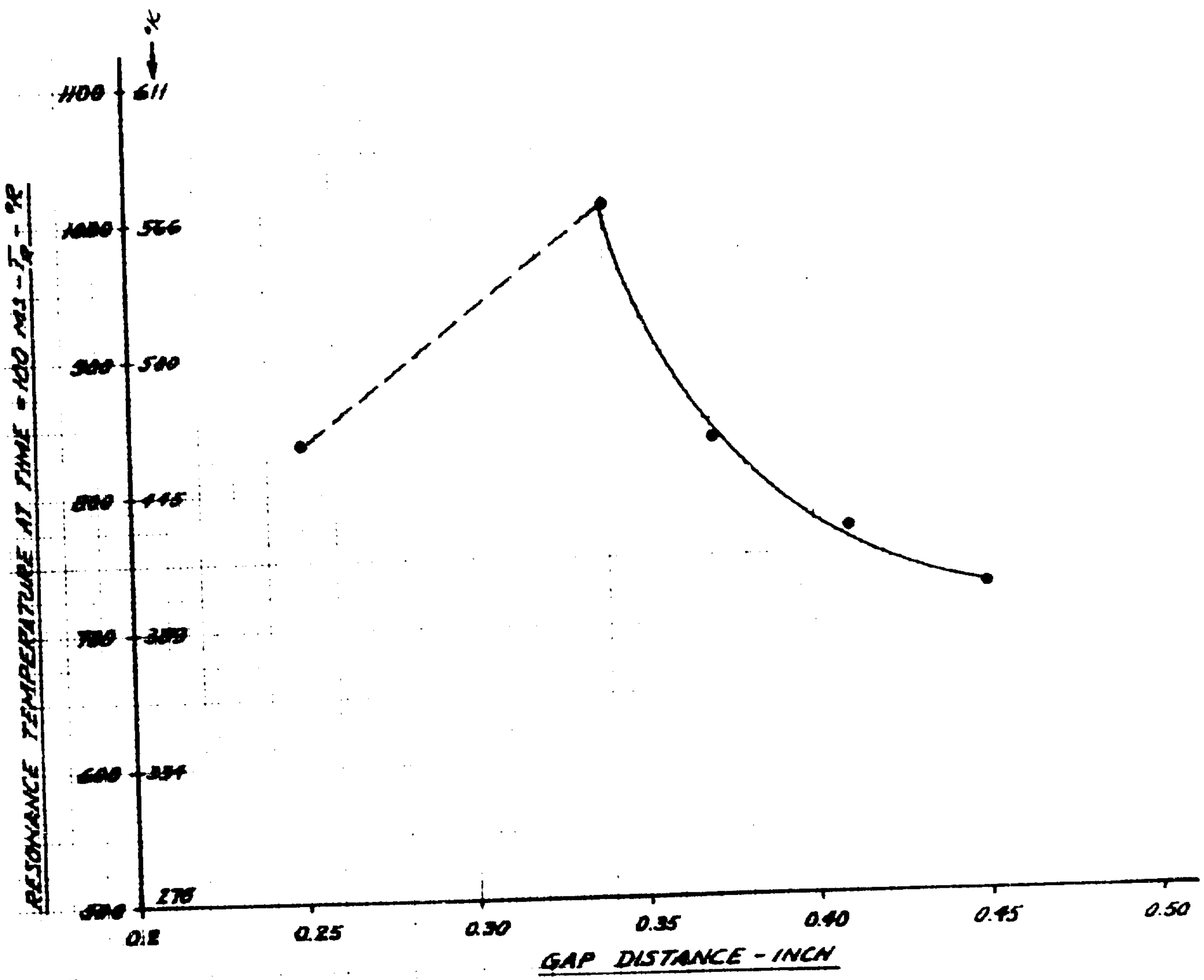

Figure 21. Resonance Igniter Geometry Optimization Resonance Tube Configuration I, Low Hydrogen Total Temperature (Gap Distance vs Resonance Temperature)

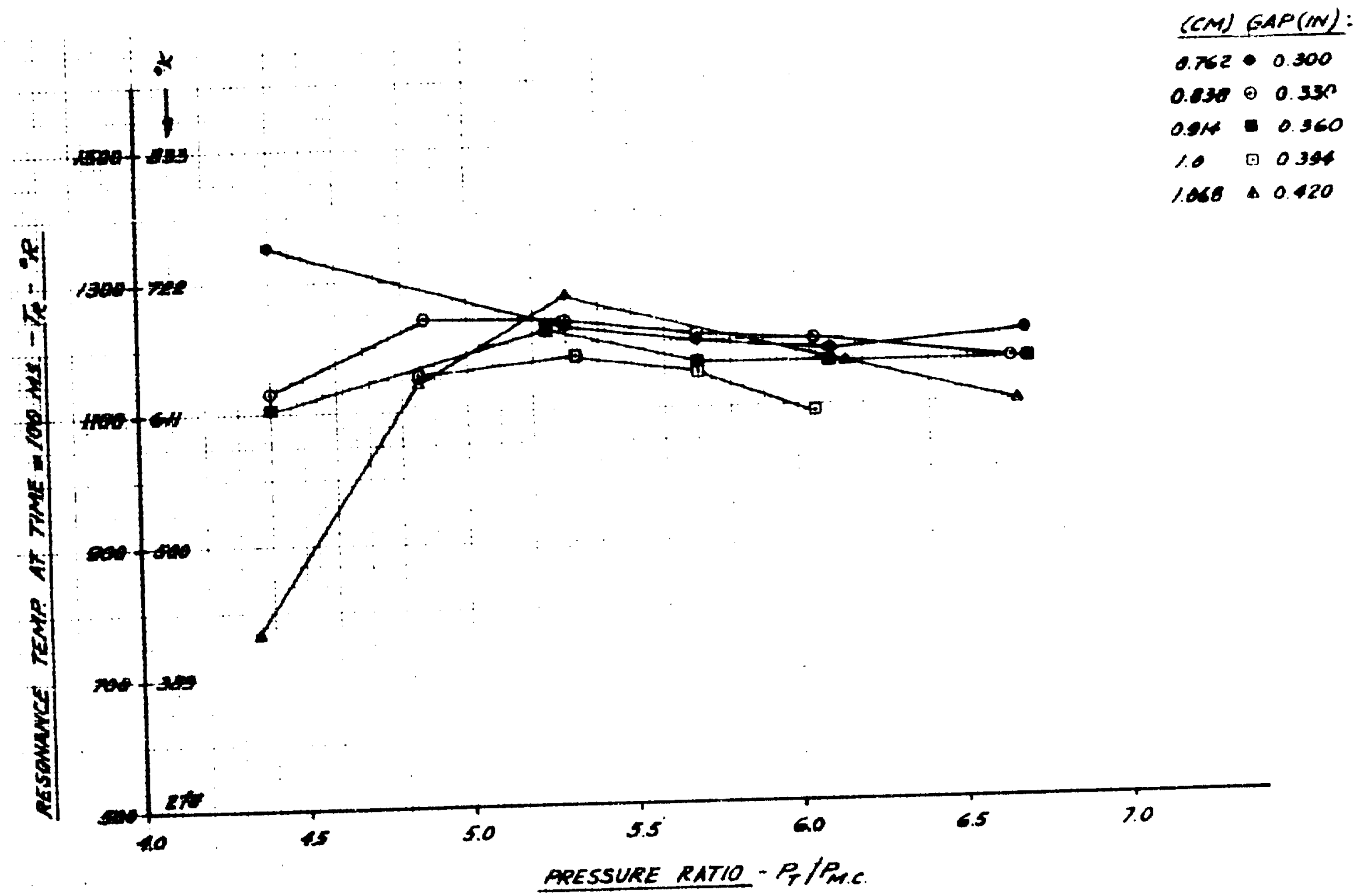

Figure 22. Resonance Igniter Geometry Optimization Resonance Tube Configuration IV, Hydrogen Total Temperature: Ambient

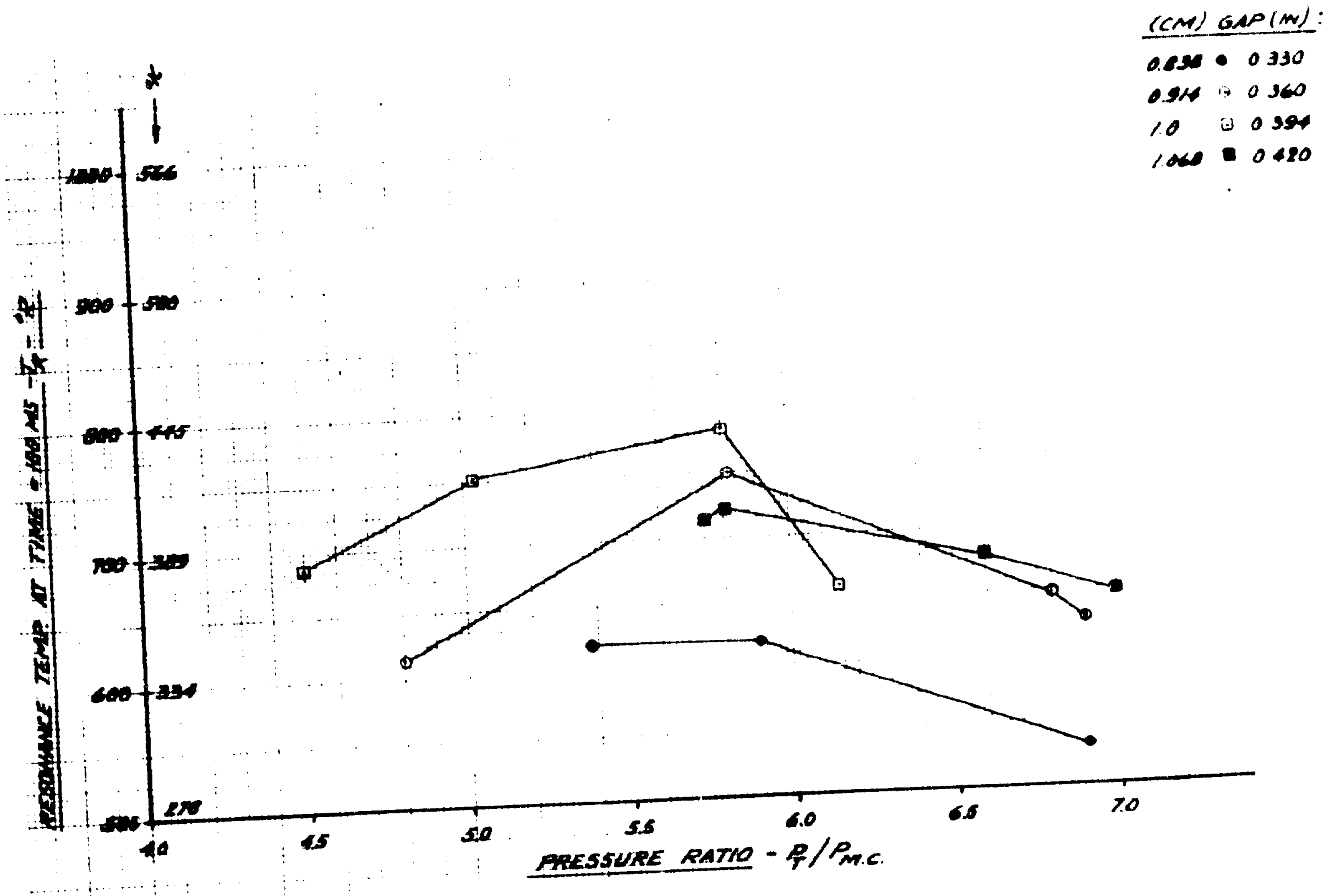

Figure 23. Resonance Igniter Geometry Optimization Resonance Tube Configuration IV, Low Hydrogen Total Temperature

TASK II - O_2/H_2 IGNITION INVESTIGATION

Igniter Configuration

Upon completion of the geometry optimization test phase, the thermocouple and its holder were replaced by a solenoid-operated valve to control the flow of oxygen into the igniter. A valve used in a previous program (Ref. 2) was redesigned to prevent leakage and to ensure that the valve seat would not come in direct contact with the quartz resonance cavity. These objectives were achieved by potting the quartz tube in a stainless-steel enclosure, and butting the valve seat with the outside surface of the enclosure. The two mating surfaces were machined flat to a mirror finish. The valve assembly shown in Fig. 24 was hydrostatically tested and no leaks were observed.

The oxygen valve and quartz tube assembly were coupled to the igniter. The gap distance was set at 0.340 in. (0.863 cm), and the Annin valve was replaced by a contoured orifice having an 0.282-in. (0.721-cm) throat diameter.

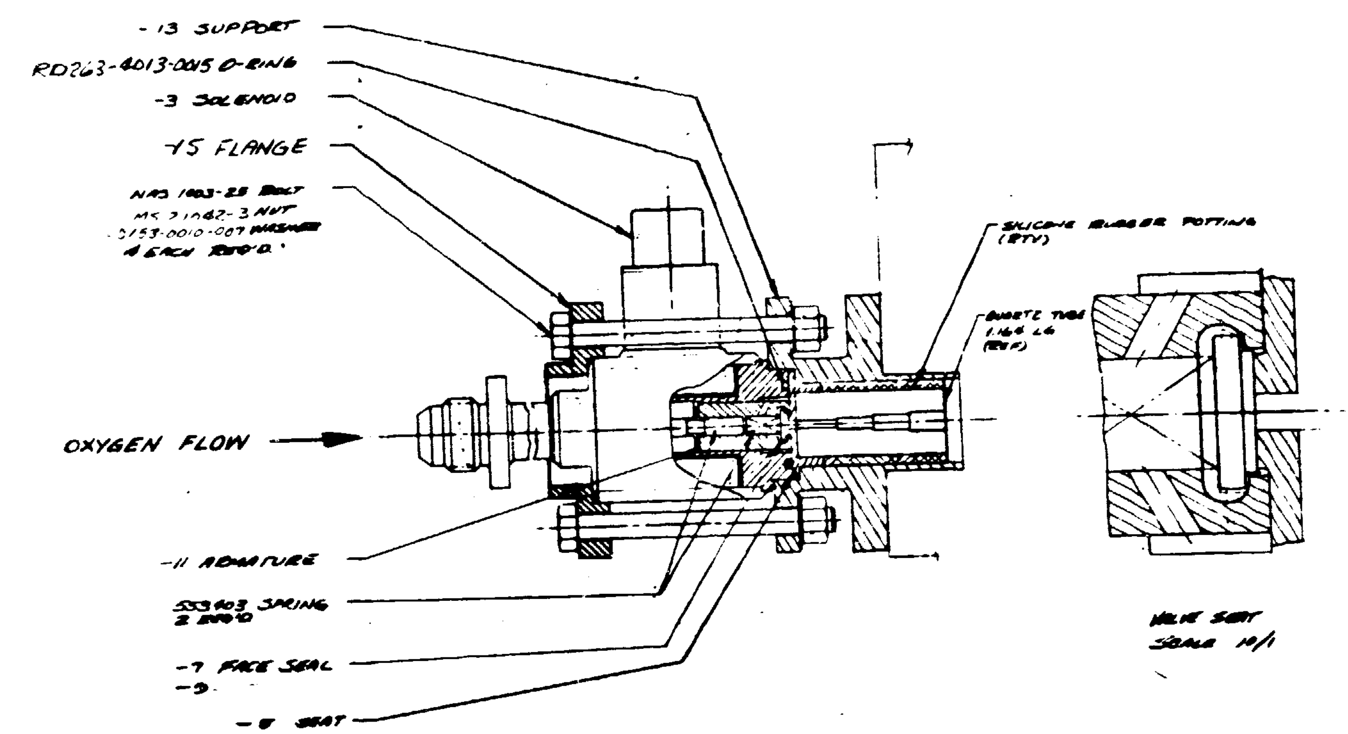

Figure 24. Solenoid-Operated Resonant Igniter Valve

Test Program

A total of 80 ignition tests were run during the program. The test facility setup and test procedure followed are described in Appendix A. The initial test series consisted of 18 tests run (see Table 9) with both oxygen and hydrogen at ambient temperature. During these tests, two types of experiments were performed: (1) keeping the o/f mixture ratio constant at approximately 0.7, the only variable was the time difference between the introduction of hydrogen and oxygen flows (72 to 0 milliseconds), (2) keeping the time difference constant, the o/f mixture ratio was varied from 0.69 to 1.33. All tests except one resulted in successful ignition. The one exception was the case where both oxygen and hydrogen were introduced into the igniter simultaneously (zero time difference), thus precluding resonance heating of the hydrogen. It should, however, be noted (Table 9) that time delays between activation of the two propellant valves could be as short as 10 milliseconds and still result in successful ignition.

A typical set of Brush recordings obtained during one of the ambient-temperature propellant ignition tests (test No. 11 in Table 9) is shown in Fig. 25.

The energy release efficiencies were calculated as a function of o/f mixture ratios for the ambient-temperature propellant tests and plotted in Fig. 26. The energy release efficiency is defined as:

$$\eta_{c^*} = \frac{c^*_{actual}}{c^*_{theor.}}$$

where

$$c^*_{actual} = \frac{P_{M.C.} A_R g}{\dot{w}}$$

$P_{M.C.}$ = mixing chamber pressure

A_R = igniter restriction

g = gravitational constant

$\dot{w}$ = total flowrate through igniter = $\left(\dot{w}_{O_2} + \dot{w}_{H_2}\right)$

TABLE 9. O_2/H_2 IGNITION TEST DATA

Test Number	P_{O_2} Inlet $\frac{N}{m^2} \times 10^4$	P_{H_2} Inlet $\frac{N}{m^2} \times 10^4$	T_{O_2} Inlet K	T_{H_2} Inlet K	$\dot{W}_{O_2}$ $\frac{Kg}{sec} \times 10^3$	$\dot{W}_{H_2}$ $\frac{Kg}{sec} \times 10^3$	Mixture Ratio $(\dot{W}_{O_2}/\dot{W}_{H_2})$	$P_{M.C.}$ $\frac{N}{m^2} \times 10^4$	Delay sec × 10^3
1	283	272	292	292	7.76	11.17	0.70	94	72
2	283	261		292	7.76	10.71	0.72	92	40
3	283	279		293	7.72	11.39	0.68	95	60
4	283	277		292	7.72	11.35	0.68	93	30
5	281	267		292	7.72	10.94	0.70	93	10
6*	281	267		292	7.72	10.94	0.70	61	0
7	279	273		292	7.72	11.21	0.69	91	23
8	318	279		294	8.81	11.39	0.77	105	
9	313	243		293	8.81	9.94	0.88	106	
10	313	236		294	8.81	9.67	0.91	105	
11	314	220		294	8.85	8.99	0.98	103	
12	313	199		292	8.81	8.17	1.08	101	
13	303	155		294	8.44	6.35	1.33	86	
14	270	153		295	7.44	6.22	1.20	80	31
15	234	153		295	6.44	6.26	1.03	73	
16	205	154		296	5.67	6.26	0.90	67	
17	175	159		296	4.68	6.49	0.72	56	
18	151	149		296	3.95	6.08	0.65	43	
19	276	289	255	216	7.90	13.80	0.57	94	60
20	275	289	267	215	7.72	13.80	0.56	93	24
21	270	239	274	221	7.63	11.26	0.68	96	
22	267	220	278	225	7.58	10.30	0.74	95	
23	269	207	278	225	7.58	9.71	0.78	96	
24	271	190	279	226	7.58	8.85	0.86	94	
25	269	180	280	229	7.58	8.35	0.91	93	
26	269	158	281	230	7.53	7.31	1.03	89	
27	272	--	226	225	8.40	--	--		
28	300	189	250	220	8.04	8.94	0.90		

* No Ignition

TABLE 9. (Continued)

Test Number	P_{O_2} Inlet $\frac{N}{m^2} \times 10^4$	P_{H_2} Inlet $\frac{N}{m^2} \times 10^4$	T_{O_2} Inlet	T_{H_2} Inlet	$\dot{W}_{O_2}$ $\frac{Kg}{sec} \times 10^3$	$\dot{W}_{H_2}$ $\frac{Kg}{sec} \times 10^3$	Mixture Ratio $(\dot{W}_{O_2}/\dot{W}_{H_2})$	$P_{M.C.}$ $\frac{N}{m^2} \times 10^4$	Delay sec × 10^3
29	286	202	266	200	7.76	9.99	0.77		24
30	271	270	239	221	8.22	12.71	0.65		
31	272	279	255	225	7.99	13.03	0.61		
32	288	262	249	222	8.08	12.30	0.66		
33	260	266	263	200	7.90	13.21	0.60		
34	272	--	259	185	7.90	--	--		
35	272	--	272	161	7.72	--	--		
36	276	313	233	152	8.35	17.79	0.47		
37	--	176	173	181	--	9.76	--		
38	191	167	179	171	6.22	8.99	0.69		
39	178	167	229	174	5.44	8.90	0.61		
40	176	182	179	170	6.17	9.76	0.63		
41	192	177	155	177	6.62	9.35	0.71		
42	180	173	177	169	6.26	9.31	0.67		40
43	180	162	167	168	6.44	8.81	0.73		40
44	188	173	192	175	6.08	9.17	0.66		100
45	155	158	201	202	4.95	7.81	0.63		48
46	169	154	216	204	4.90	7.58	0.65		100
47	189	149	232	213	4.81	7.13	0.68		
48	161	163	241	207	4.67	7.94	0.59		
49	161	169	249	209	4.54	8.22	0.55		
50	226	165	256	219	6.54	7.85	0.83		
51	220	164	259	199	6.49	8.17	0.79		
52	222	161	258	196	6.49	8.08	0.80		50
53	218	161	262	168	6.40	8.72	0.73		37
54	219	160	262	195	6.40	8.08	0.79		37
55	223	167	262	193	6.40	8.44	0.76		37
56	211	164	272	205	6.17	8.03	0.77		

TABLE 9. (Concluded)

Test Number	P_{O_2} Inlet $\frac{N}{m^2} \times 10^4$	P_{H_2} Inlet $\frac{N}{m^2} \times 10^4$	T_{O_2} Inlet K	T_{H_2} Inlet K	$\dot{W}_{O_2}$ $\frac{Kg}{sec} \times 10^3$	$\dot{W}_{H_2}$ $\frac{Kg}{sec} \times 10^3$	Mixture Ratio $(\dot{W}_{O_2}/\dot{W}_{H_2})$	$P_{M.C.}$ $\frac{N}{m^2} \times 10^4$	Delay sec $\times 10^3$
57	244	169	273	196	6.26	8.44	0.74		30
58	223	153	215	199	5.40	7.63	0.71		30
59	235	149	243	200	5.08	7.35	0.69		84
60	189	143	174	200	5.95	7.08	0.84		[illegible]
61	180	140	175	189	5.99	7.17	0.84		84
62	160	147	155	182	6.31	7.63	0.83		84
63	200	153	154	192	6.35	7.76	0.82		84
64	201	141	153	189	6.35	7.22	0.88		[illegible]
65	191	180	148	172	6.40	9.62	0.66		84
66	187	172	182	178	5.90	9.03	0.65		84
67	156	167	192	178	5.72	8.81	0.65		84
68	158	176	223	164	5.26	9.62	0.55		84
69	189	202	153	153	6.26	11.44	0.55		[illegible]
70	185	198	148	150	8.22	11.30	0.73		92
71	194	196	146	141	8.26	11.58	0.71		[illegible]
72	209	209	148	167	8.22	11.39	0.72		[illegible]
73	216	197	140	169	8.40	10.62	0.79		92
74	224	187	153	152	8.03	10.62	0.76		[illegible]
75	298	134	153	192	10.76	6.81	1.58		[illegible]
76	286	143	145	188	10.98	7.31	1.50		[illegible]
777	297	165	164	190	10.71	8.35	1.28		[illegible]
78	287	146	180	194	9.94	7.35	1.35		[illegible]
79	284	176	148	169	10.89	9.49	0.83		[illegible]
80	260	170	143	167	11.08	9.26	1.20		[illegible]

NOTES:
1. All tests conducted with Resonance Tube Configuration IV, gap = 0.00864 m, and restriction diameter = 0.00716 m.
2. Delay column indicates time difference between opening of hydrogen inlet valve and oxygen inlet valve.
3. All tests resulted in ignition, except Test No. 6.
4. Where mixing chamber pressure ($P_{M.C.}$) is not given, indicates unsteady oxygen inlet flowrate condition.

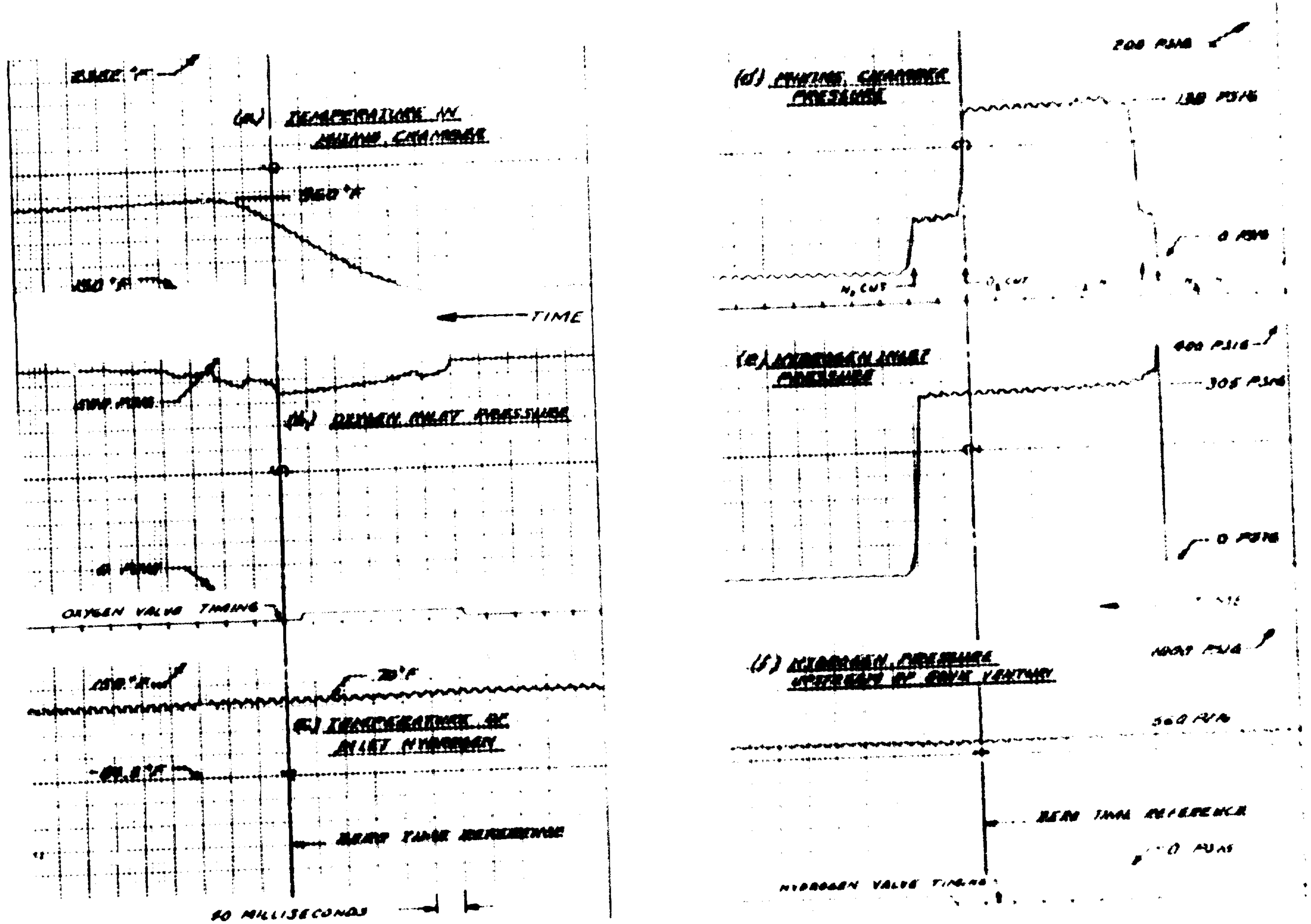

Figure 25. Typical Brush Record of Ignition Test (Ambient-Temperature

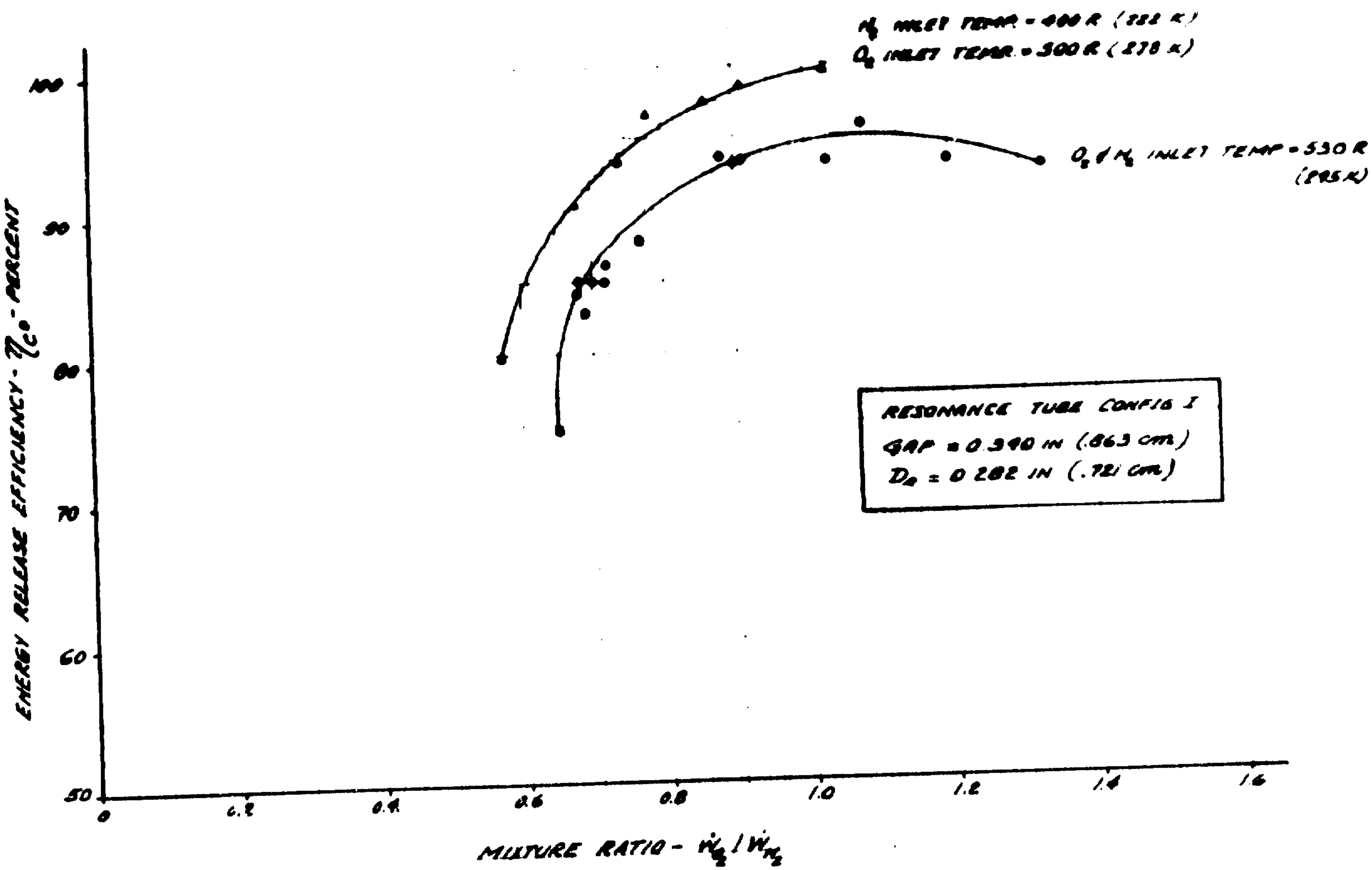

Figure 26. Energy Release Efficiency Versus Mixture Ratio

From Fig. 26 it is interesting to note that maximum η_{c*} occurs near a mixture of 1, which was the original design point of the igniter.

Following the ambient-temperature propellant tests, liquid nitrogen was supplied to the oxygen and hydrogen heat exchangers, and ignition tests were performed with progressively lower propellant temperatures at the igniter inlet.

The oxygen inlet temperature was varied from 506 R (281 K) down to 256 R (142 K) and the hydrogen inlet temperature was varied from 415 R (231 K) down to 254 R (141 K). The objective of achieving 200 R (111 K) for both propellant inlet temperatures could not be achieved due to under-capacity of the heat exchangers. During many of the tests conducted at low temperatures, the flow of oxygen became unsteady. The program schedule did not permit a full investigation of the reasons for the unsteadiness, however, it can be hypothesized that the cause was principally due to the oxygen feed system characteristics. A flow restriction (orifice) placed between the exit of the heat exchanger and the igniter inlet valve (see Fig. A-1 in Appendix A) would have allowed exact oxygen flowrate measurement right at the igniter and may have prevented the potential flow accumulation (due to density changes) in the heat exchanger and igniter pressure feedbacks into the oxygen line. Since the oxygen flowrate was measured upstream of the heat exchanger, pressure disturbance (hence flowrate) at the igniter could not be sensed at the sonic venturi.

A typical set of Brush records taken during one of the low-temperature propellant tests (test No. 65 in Table 9) is shown in Fig. 27. The pressure oscillations at the oxygen inlet and in the mixing chamber are evidenced in Fig. 27b and 27d. The first pressure peak in the mixing chamber is due to the ignition of residual oxygen present in the chamber before the opening of the igniter oxygen valve. In this particular case, cold oxygen was introduced into the igniter prior to testing in order to cool the igniter body down to the temperature of the propellants so as to prevent heat "soak-back" into the gases during ignition tests. In spite of the fact that precooling with oxygen had been stopped 1 to 2 seconds

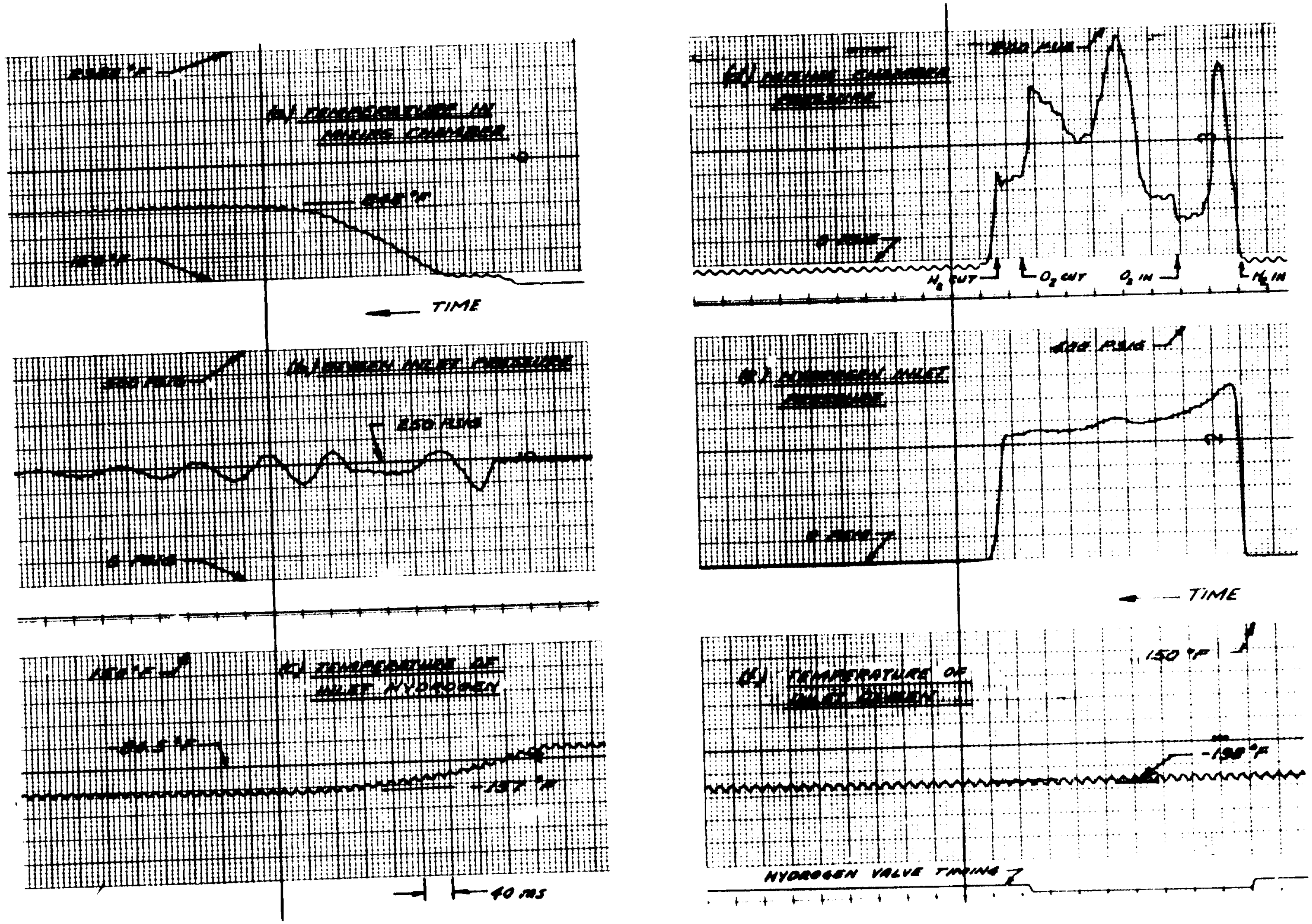

Figure 27. Typical Brush Record of Ignition Test (Low Temperature Oxygen and Hydrogen)

before ignition testing, the vacuum system did not evacuate all of the oxygen from the igniter. Subsequent tests performed without the hardware precooling procedure just described, showed that (1) the preignition of residual oxygen did not affect the ignition characteristics during the main propellant flow, and (2) the oxygen inlet pressure oscillations remained unaltered. The flowrates indicated in Table 9 are the average flowrates measured upstream of the heat exchangers.

A total of 62 tests were made with low-temperature oxygen and hydrogen, and all tests resulted in igitions. During the previous program (Ref. 2), 12 of the 23 low-temperature tests performed (O_2 and H_2 temperatures ranging from 416 R (231 K) to 281 R (156 K), 12 of the 23 low-temperature tests did not result in ignition. Although these tests were conducted with the same igniter hardware, its critical dimensions were sized for ambient-temperature operation. Consequently, the present program demonstrated that with proper geometrical optimization, the resonance igniter can be used as a reliable ignition device for low-temperature oxygen and hydrogen propellants.

Summary of O_2/H_2 Ignition Investigation

1. All tests performed with low-temperature oxygen and hydrogen resulted in successful ignitions. The oxygen inlet temperature was varied from 506 R (281 K) down to 256 R (142 K), and the hydrogen inlet temperature was varied from 415 R (231 K) down to 254 R (141 K).
2. Oxygen flow instabilities occurring only during low-temperature tests (due to feed system arrangement) did not permit accurate oxygen flowrate measurements.
3. The test program demonstrated that geometry optimization of the resonance igniter for low-temperature operation significantly improved the ignition reliability.

CONCLUSIONS

TASK I: SYSTEM ANALYSIS

1. The resonance igniter offers a competitive weight advantage over spark igniter (ASI) in propulsions systems where oxygen and hydrogen are used as propellants. Resonance ignition is particularly attractive in applications where multiple and/or repetitive ignitions are required, and where radio interference has to be eliminated.
2. The application of the resonance igniter for short pulse monopropellant thrustors does not appear to be practical because of a) the need for gasification or a gas carrier (the monopropellants being generally stored as liquids), and b) the relatively long resonance heating time period of high molecular weight fluids.

TASK II: EXPERIMENTAL STUDIES

1. The internal geometry of the resonance igniter can be optimized for low temperature O_2/H_2 bipropellant operation.
2. With an optimized resonance igniter configuration, successful and reliable ignitions of O_2/H_2 can be achieved over a wide range of O_2 and H_2 inlet temperatures and inlet pressures.

RECOMMENDATIONS

1. Analytical and experimental efforts should be directed toward gaining a fundamental understanding of gas-dynamic resonance heating and ignition processes.

2. An experimental program is needed to determine the resonance ignition characteristics of monopropellants.

3. A program is needed to develop a fixed geometry prototype resonance igniter for O_2/H_2 bipropellant. This program should include reliability studies, cooling and flow augmentation studies.

4. The fixed geometry prototype resonance igniter should be tested in conjunction with a breadboard engine to study ignition/engine transient and steady state operating characteristics.

NEW TECHNOLOGY

Descriptive Title: Low Temperature O_2/H_2 Resonance Igniter.

An igniter operating on the principle of gas-dynamic resonance was developed for operation with low temperature oxygen and hydrogen in their gaseous state.

Name of Innovator: L. Stabinsky

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APPENDIX A

DESCRIPTION OF TEST FACILITY

PROPELLANT FEED SYSTEMS

Feed systems for both propellants, oxygen and hydrogen, were similar in size and configuration. Each gas was stored in a high-pressure bottle bank and fed to the test cell by a 1-1/2-inch system and pressure regulator. A schematic of the resonance igniter test facility is shown in Fig. A-1. The sonic venturis shown in Fig. A-1 were calibrated Flowdyne models which were plumbed in each propellant line to measure propellant flowrates. Flowdyne nozzles were of the converging-diverging type design. Operating on the principle of critical compressible flow, only the inlet pressure and temperature were needed to determine the gas flowrate. The propellant flowrates varied linearly with the upstream pressure and were not affected by downstream pressure fluctuations.

Downstream of the venturi was an aluminum heat sink heat exchanger, designed to provide conditioned propellant to a given temperature from 200 (111) to 800 R (444 R). The heat exchanger had a propellant coil, liquid nitrogen coil, and electric heating coil embedded within an aluminum casting. Cold-temperature conditioning was achieved by flowing liquid nitrogen and using the heating coil in an on/off mode to achieve fine control of the aluminum-block temperature. Hot temperature conditioning was achieved by using the heating coil only. During ambient-temperature tests, the heat exchanger was bypassed to eliminate the heat exchanger pressure drop. Since hydrogen is difficult to cool due to its high heat capacity, additional cooling provisions were made on the hydrogen circuit. This was accomplished by placing a precooler, consisting of a 6-foot-long tube in shell line, upstream of the aluminum heat sink exchanger. Downstream of the heat exchanger the system was close-coupled to reduce system mass and time required to temperature condition the hardware. Close-coupled to the igniter valves was a low pressure drop subsonic venturi to measure transient and steady-state flowrate and a bleed point to precondition the system temperature up to the valve inlet. Figure A-2 is a photo of the igniter test facility showing the resonance igniter installed with the close-coupled oxygen valve.

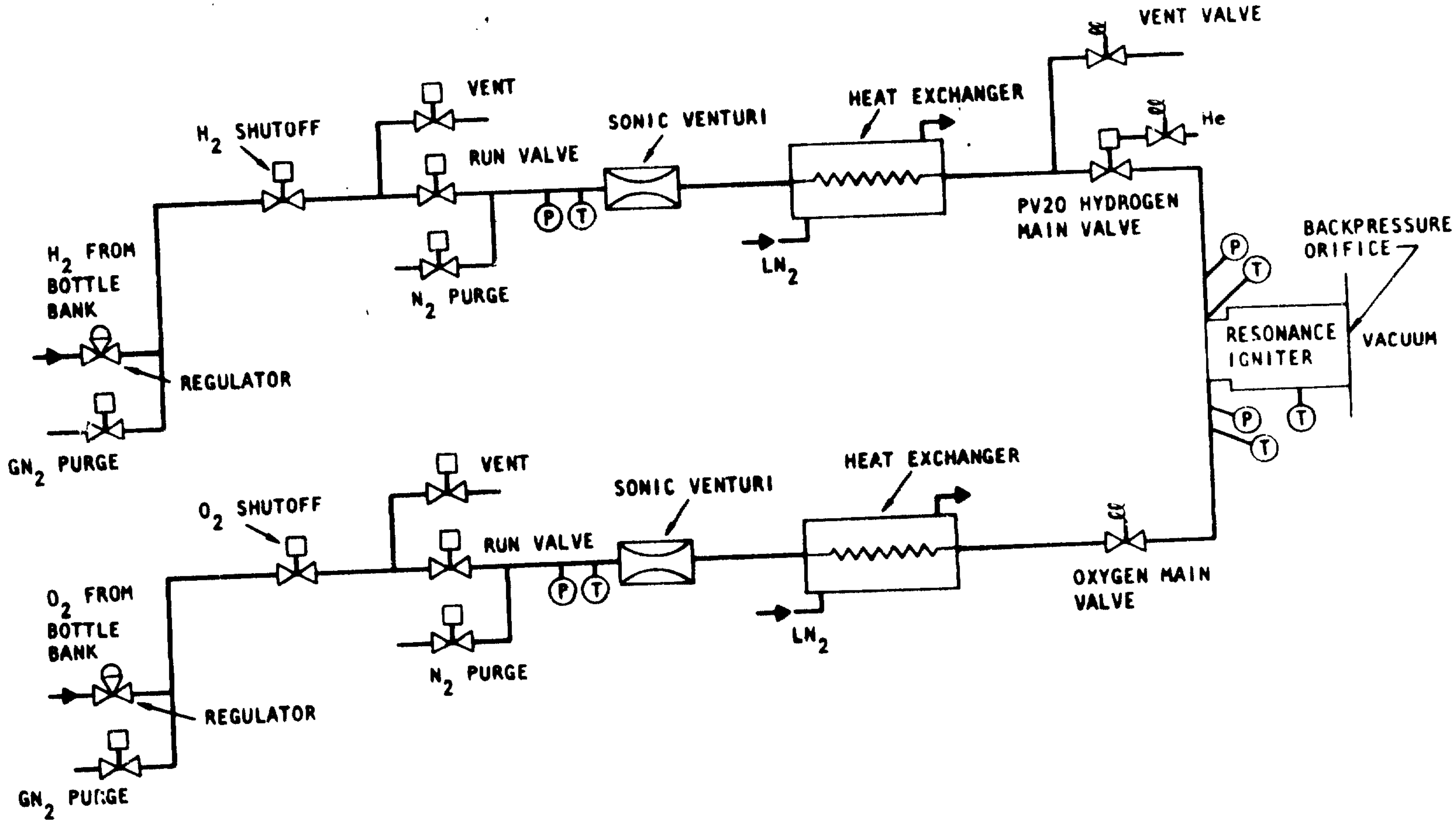

Figure A-1. Resonance Igniter Test Facility Schematic

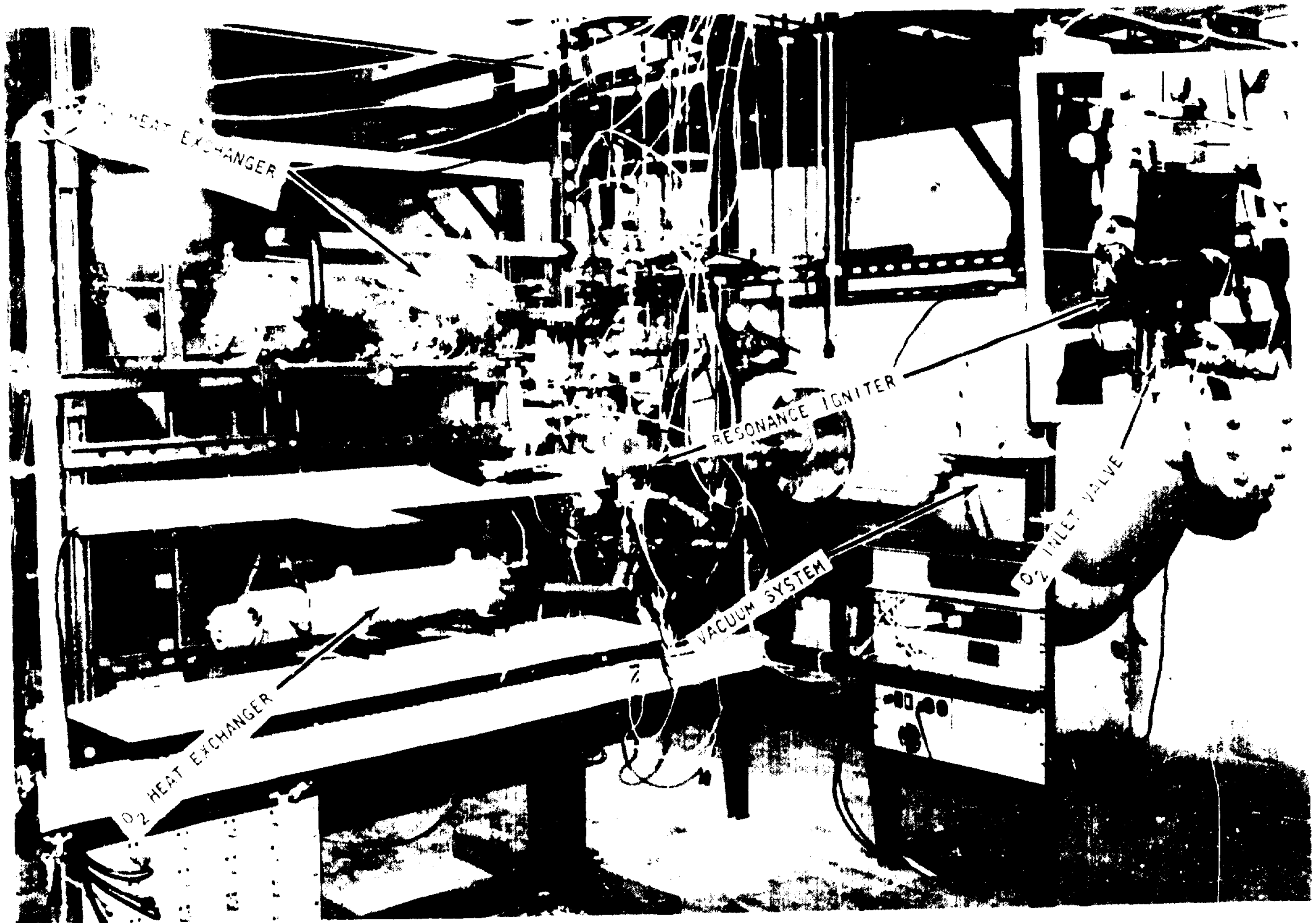

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Figure A-2. Resonance Igniter Test Setup

SYSTEM CONTROL

All tests were conducted using an automatic sequencer. The sequencer allowed operation of the fuel valve, oxidizer valve, and fuel bleed valve. The sequencer was capable of controlling the valves to any specified relative position in time within 1 millisecond. Prior to each test series, the sequence was verified with the systems pressurized with GN_2.

A continuous flow of hydrogen at approximately the test flowrate was maintained through a vent immediately upstream of the igniter valve. In this manner, the specified propellant temperature and pressure was maintained at the valve inlet. During the test, the vent valve was sequenced closed immediately before the igniter valve was sequenced open.

INSTRUMENTATION

Pressure and temperature sensors were used to establish and monitor system and hardware conditions. Data acquisition included a high-speed digital system, a high-frequency oscillograph recorder and a six-channel high-response Brush recorder. Dial indicators were located on the control console (Fig. A-3) for system setup.

The digital system was an Astro Data System capable of 6600 samples per second with inputs from up to 100 sensors. Since the necessary instrumentation required less than 25 inputs, each parameter was multiplexed four times to achieve a sample rate of 264 times per second per parameter. The Astro Data System recorded data on magnetic tape for subsequent computer data reduction on an IBM 360.

Data from a high-frequency Kistler water-cooled transducer, along with other selected system parameters were also recorded on a high-frequency oscillograph to establish the transient conditions and ignition delay. This recorder produced permanent strip charts at speeds up to 128 inches per second.

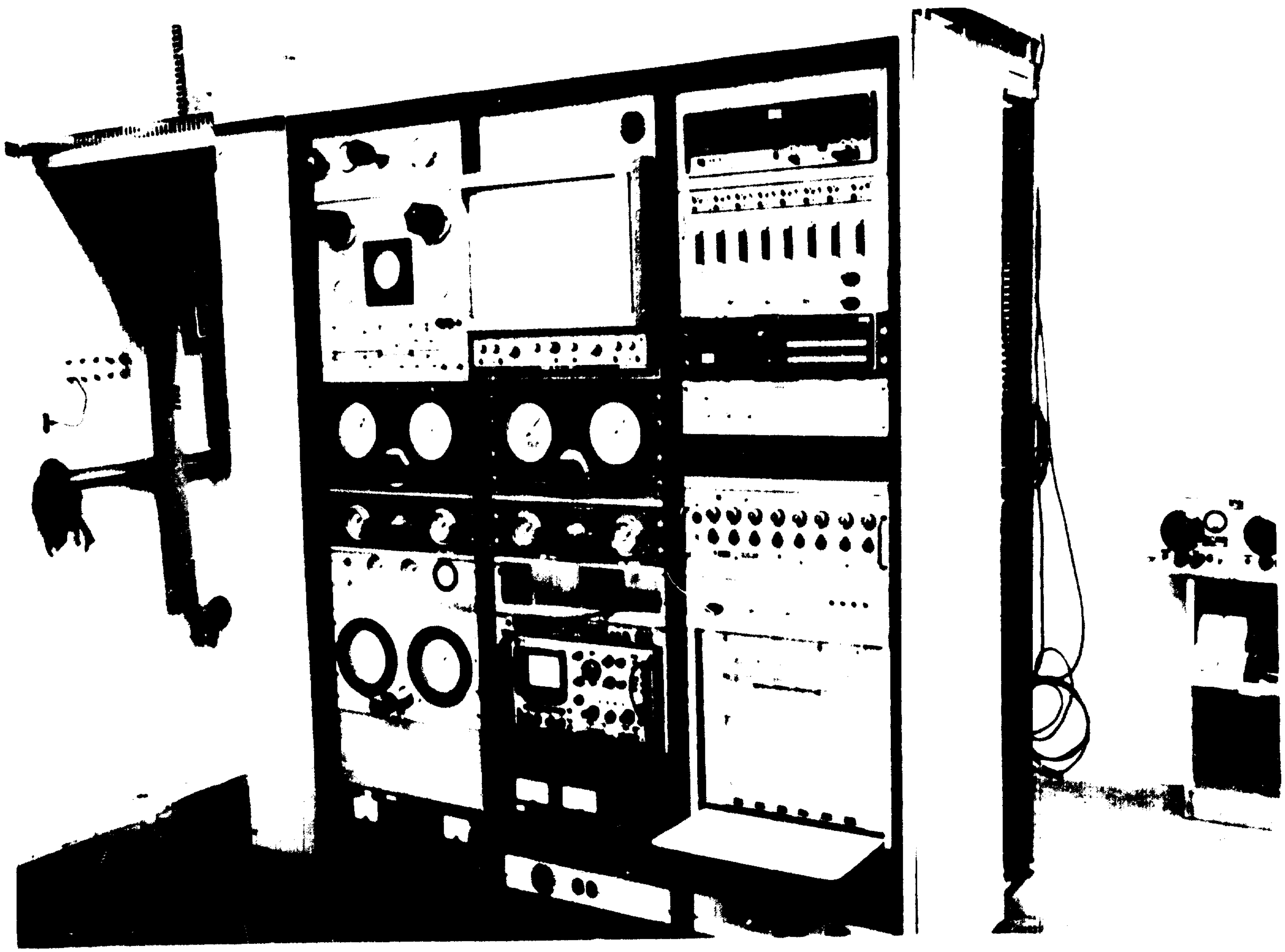

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Figure A-3. Resonance Igniter Instrumentation Panel

A six-channel Brush recorder was used for on-the-spot monitoring of test results. This recorder was capable of high response and accurate quantitative data. In addition, the Brush recorder contained channels for recording the electrical valve sequence. Figure A-3 is a photo of the instrumentation panel built up for the program.

TYPICAL OPERATING PROCEDURES

The steps described below were typical of the procedure followed during the program:

1. Install desired resonance igniter configuration
2. Set backpressure orifice downstream of igniter to desired value
3. Adjust electronic valve timer so that bleed valve is closed and fuel flow leads oxidizer by desired amount
*4. Chill down heat exchangers with liquid nitrogen
5. Depending on desired injection pressure and/or flowrate, determine H_2/O_2 pressure settings upstream of each sonic venturi
6. Set fuel, oxygen, and purge pressures
*7. Flow cold oxygen through system and igniter by opening oxidizer main valve
*8. Flow cold hydrogen through system by opening bleed valve upstream of main valve
9. Run test
   a. Turn on Brush chart drive manually
   b. Open fuel bleed valve
   c. Turn on electronic sequence start which automatically closes fuel bleed valve, opens fuel main valve, opens oxidizer main valve, then closes oxidizer and fuel main valves
   d. Turn off Brush chart drive manually

*Steps 4, 7, and 8 for cold-propellant runs only; these steps were omitted during ambient-propellant tests.

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